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(54) Title: ILLUMINATION DEVICE AND METHOD FOR LASER PROJECTOR

(57) **Abstract:** Systems and methods for providing illumination suitable for imaging devices such as laser projection systems. In one embodiment, a highly collimated (e.g., laser light) beam is passed through a holographic diffuser to create a well defined cone angle for the light emanating from each point on the diffuser. This light is focused into an illumination image that is controlled by the prescription of the diffuser. In one embodiment, the image is a uniformly intense rectangle having a 4:3 aspect ratio to match an imager for a projection display. The diffuser prescription and resulting illumination image can be selected to match any desired imager. The present systems and methods may provide the advantages of high level of light efficiency, reduction or elimination of speckle and "worminess" and reduction or elimination of cosine^4 and gaussian intensity falloff, all of which are common in prior art designs.

DESCRIPTION

ILLUMINATION DEVICE AND METHOD FOR LASER PROJECTOR

RELATED APPLICATIONS

This application claims the benefit of the following U.S. provisional applications under 35 U.S.C. 119(e), which are fully incorporated by reference as if fully set forth herein.

Serial No. 60/257,061, filed on December 20, 2000 entitled "Method and Apparatus for Combining Parallel Collimated Lightbeams", Attorney Docket No. RIAKE1100;

Serial No. __________, filed on August 1, 2000 entitled "Illumination Device and Method for Laser Projector", Attorney Docket No. RIAKE1110;

Serial No. 60/257,047, filed on December 20, 2000 entitled "Method and Apparatus for Combining Parallel Collimated Lightbeams", Attorney Docket No. RIAKE1120;

Serial No. 60/257,062 filed on December 20, 2000 entitled "Method and Apparatus for Eliminating Zero-Order Light Leak in an Illumination Device", Attornry Docket No. RIAKE1130;

Serial No. 60/257,063, filed on December 20, 2000 entitled "Method and Apparatus for Providing an Illumination Source Using a Segmented Diffuser"; Attorney Docket No. RIAKE1140;

Serial No. 60/257,045, filed on December 20, 2000 entitled "Method and Apparatus for Combining Polychromatic Light Beams Using an Achromatic Diffuser, Attorney Docket No. RIAKE1150;

Serial No. 60/257,046, filed on December 20, 2000 entitled "Illumination Device Using Multiple Laser Light Sources and Having Zero-Order Light Leak Correction, Attorney Docket No. RIAKE1160;

Serial No. 60/284,455, filed on April 18, 2001 entitled "Method and Apparatus for Providing Selectable Illumination Sources", Attorney Docket No. RIAKE1170;

Serial No. 60/282,738 , filed on April 10, 2001 entitled "Polychromatic Display Device Using Monochromatic Diffusers, a Beamsplitter and a Combiner in an Optical Processor Space", Attorney Docket No. RIAKE 1200;

Serial No. 60/282,736, filed on April 10, 2001 entitled "Method and Apparatus for Combining Multiple Monochromatic Images Using an Optical Processor Space", Attorney Docket No. RIAKE1210;

Serial No. 60/282,735, filed on April 10, 2001 entitled "Monochromatic Display Device Using a Monochromatic Diffuser and a Beamsplitter and a Combiner in an Optical Processor Space", Attorney Docket No. RIAKE1250;

Serial No. 60/282,737, filed on April 10, 2001 entitled "Polychromatic Display Device Using a Chromatic Combiner, and Achromatic Diffuser and a Beamsplitter and a Combiner in an Optical Processor Space", Attorney Docket No. RIAKE1260; and

Serial No. 60/282,734, filed April 10, 2001 entitled "Polychromatic Display Device Using Monochromatic Diffusers, a Beamsplitter and a Combiner in an Optical Processor Space", Attorney Docket No. RIAKE1270;

FIELD OF THE INVENTION

The invention relates to projection displays and more particularly an improved method of homogenizing and formatting the light from a light source to produce higher uniformity and efficiency in the projected image.

DESCRIPTION OF RELATED ART

Illumination systems used for image projectors are designed to generate a spatially uniform plane which can be used to illuminate an imaging device, film or other media. The reflected or transmitted light from the imaging device is then projected onto a screen for viewing. The brightness and spatial brightness uniformity should be within certain limits for each particular application to be considered acceptable to the viewers.

Image projectors including film movie projectors, slide projectors, electronic liquid crystal and micro-electro-mechanical (mem) projectors, microfilm and overhead projectors all require a high degree of spatial light uniformity in the image to produce a pleasing image. This has always been a challenge for projection system designs due to the fact that the light sources available for these systems all have very disorganized light output and therefore require complex optical systems to organize the light. Additionally, high degrees of magnification in short distances (which often occur in these optical systems) cause a problem which is well known in the optical field -- the $\cos^4$ roll off of power in the image as you move radially away from the center of the image. This effect is most predominant at the corners of the image. Another problem is that light sources tend to produce round or elliptical gaussian beam profiles, while most images are rectangular in format. Typically, the light beam is spatially truncated (i.e., the portions of the beam which fall outside a rectangular profile that corresponds to the image are blocked). This leads to another problem, which is maximizing the brightness of the illumination -- when the light is truncated to change its geometry, the truncated light is obviously wasted.

Many optical methods have been used in the prior art to try to minimize the variations in uniformity which are due to the particular characteristics of the available light sources as well as to maximize the brightness of the illumination. The optical method used depends somewhat on the light source used. Many different types of light sources are in common use today. Some types are electric filament, and arc lamps including metal halide arc, low and high pressure mercury arc, xenon arc, carbon arc, as well as solid state Light Emitting Diode (LED) sources, and Lasers. Not all of these light sources, however, are suitable for displays using prior art technologies.

Two of the most common types of light sources in use in commercial applications are metal halide arc lamps and high pressure mercury arc lamps. These arc lamps are usually configured in an optical illumination system which employs an elliptical or parabolic reflector to gather and direct the light to a focal point or collimated beam respectively, as shown in FIGURE 1. Both of these types of systems produce highly non-uniform beams. Some systems use reflective tunnels or light pipes through which the source light is channeled in order to create a scrambled, hence more spatially uniform bundle of light rays as shown in FIGURE 2.

Lenslet arrays are also sometimes used to increase the uniformity of the light. Some versions of these lenslets are described in U.S. Pat. 5,098,184 and U.S. Pat 5,418,583. The lenslet arrays function essentially in the following manner. Two lenslet arrays are separated by a distance equal to the focal length of the individual elements. The elements of the first array form an image of the source in the aperture of the elements of the second array. In the case of a laser, the source image is a diffraction pattern. The elements of the second array then form an image of the aperture of the elements of the first array on the illumination plane. The aperture is chosen to match the aspect ratio of the device (film gate, or LCD) to be illuminated. A field lens in close proximity to the second array focuses the chief rays of each element to the center of the illumination plane so that the subsets of the beam sampled by all elements of the arrays are superimposed at the illumination plane and an averaging process thus occurs that causes the illumination plane to have more uniform irradiance. A second field lens is often required at the illumination plane to ensure that the light is telecentric as most often required by projection imaging optics.

In this manner a beam with non-uniform irradiance may be sampled by arrays composed of many elements and converted to a uniform beam with a different geometry (generally rectangular).

The lenslet array optical system which is used in an illumination system has design characteristics that must be adjusted to ensure that the illumination and imaging systems are compatible. If they are not, then light is wasted. For example, the geometry of the illumination should be the same as the geometry of the imager. The numerical aperture of the illumination system should also be compatible with the imaging system. The ratio of the footprint of light incident on the first array to the distance to the illumination plane determines the numerical aperture of the illumination light. Thus the focal length of the array elements and the field lens focal lengths are adjusted to ensure that the illumination numerical aperture matches the imaging numerical aperture.

At first blush, laser light appears to have enormous potential for being the illumination source in projection display systems. The light is well behaved and organized (ie: it is collimated), it is chromatically pure, and with a minimum of three wavelengths (Red, Green, and Blue) a high color space or gamut can be created, and high power low cost lasers are becoming available. There are, however, several problems with laser-based illumination systems.

First, the coherency of laser light leads to speckle, which is a fine-grained non-uniformity. The speckling effect is increased with the use of so-called holographic diffusers as proposed in this invention. The net effect is often a high frequency mottling effect sometimes called "worminess." Another problem is that the laser light is collimated and, as such, it is difficult to create a cone or numerical aperture which will allow an image to be projected onto a screen, as with a projector. Yet another problem is that the laser light typically has a gaussian intensity profile and it may have a wide range of diameters, depending upon the particular laser source which is used. This can, and often does, lead to a non-uniform light distribution on the final screen or projected image surface.

Another problem is that currently available lasers typically do not have enough power to provide sufficient illumination in some display devices. Further, using prior art methods, it is difficult to combine the beams of multiple lasers to obtain sufficient illumination for this purpose.

Another problem with the use of laser light as a display illumination device is that the beam generated by a laser may be astigmatic in its divergence. In other words, the divergence in the beam's cross section may be greater in one axis than another. This causes additional processing problems compared to a circularly symmetric diffraction limited beam.

Yet another problem with the use of laser light in a display illumination device is that, if laser light is diffracted in an optical system, a certain amount of light passes through the diffracting device without being diffracted. This effect is referred to as zero-order light leak. Zero-order light leak may prevent the resulting diffraction pattern from conforming to a well-defined, desired function.

Another problem with using laser light sources for illumination is that they are monochromatic. Since it is desirable to have a source of white light, it may be necessary to combine laser light beams of several different wavelengths (e.g., red, green and blue.) This may be difficult because many optical systems and components are wavelength-dependent and may therefore require color correction to provide even illumination.

Another problem with the use of laser light in display systems is that a large physical volume is normally required. The space requirements of these systems results in part from the separate processing of the laser illumination light in a first optical system and the subsequent processing of the image information in a second optical system so that it can be displayed for viewing.

Yet another problem with the use of laser light in a display illumination device is that optical processors for formatting the illumination image from the laser source are configured to provide a single fixed illumination aspect ratio format . To obtain a different aspect ratio format for use in the display, the illumination source is typically masked, so a portion of the light is lost and significant system efficiency is lost. In order to utilize all of the light generated by the laser source, it may therefore be necessary to use an entirely different optical processor.

SUMMARY OF THE INVENTION

One or more of the problems outlined above may be solved by the various embodiments of the invention. The present invention performs a similar function as a lenslet array optical system, but does so more effectively, with fewer and lower cost components, and with improved design flexibility. The present techniques may be applied to many types of illumination sources such as arc lamps and LED's in addition to lasers.

Broadly speaking, the invention comprises a system and method for converting a laser beam having a non-uniform profile into a source of illumination which has uniform power density. The generated illumination image may be used for a variety of purposes. For example, the image may be a uniformly intense rectangle suitable for use in a display device, or it may be a round dot suitable for transmitting the light into an optical fiber. The present invention can be used to conserve the power generated by the laser source and direct substantially all of the power into the desired illumination region. Laser speckle artifacts can also be reduced or eliminated at the same time. The choice of design of the elements in the system allows for precise control of the illumination pattern and the particular telecentric cone angle patterns exiting the illumination pattern. While the preferred embodiment uses a laser source, the system is capable of utilizing a wide variety of light source devices, including all arc lamps and LED sources.

The operation of a system in accordance with one embodiment of the invention is as follows. A block diagram of the system is shown in FIGURE 4. A beam of light is first generated by the laser light source. The light beam is expanded or sized to illuminate a controlled angle diffuser. The expanded beam remains collimated.

The expanded beam is passed through a controlled angle diffuser (e.g., hologram, bulk scatterer, etc.) to diffract or direct the light in a predetermined pattern. (Crossed lenticular arrays, or lenslet arrays can also be used.) The controlled angle diffuser can be designed to emit light angularly in any geometry (such as rectangular to match a display device aspect ratio). The angular emission of a holographic diffuser is similar to the aperture geometry of the lens array system described above. It should be noted, however, that in the prior art it takes two optical elements with an intervening space to produce an effect which is performed by a single optical element (the holographic diffuser) in the present system.

A first field lens is positioned following the holographic diffuser. This first field lens focuses and spatially overlays the diffracted light onto a single rectangular plane which lies at a distance from the lens equivalent to its focal length. A second field lens is used at this illumination plane to correct for the degree of telecentricity desired in the system. In some cases, over-correction or under-correction may be desired. This image is then used as the illumination source for a display. Both field lenses function identically to field lenses in lens array systems, but at significantly lower cost.

The present systems and methods may provide a number of advantages over prior art. For instance, the level of light efficiency may be substantially increased over the prior art. Further, the problems often encountered in coherent optical systems relating to speckle and image "worminess" (high frequency intensity variation) may be reduced or eliminated. Another advantage is that the illumination provided in this manner is uniform and can be spatially formatted to match the display device being illuminated (rather than providing illumination with the gaussian intensity falloff which is common in prior art designs).

An alternative to the holographic diffuser is a crossed lenticular array as shown in FIGURE 5A. The crossed lenticular array performs the same optical function as the hologram for a rectangular emission profile, but at a lower spatial sampling rate. The lens profiles in the lenticular can be aspheric to compensate for uniformity issues as described above. The crossed lenticulars can be combined into one element as shown in FIGURE 5B. An additional configuration is to integrate the crossed lenticular function into a single element lenslet array as shown in FIGURE 5C. While the lenslet arrays reduce the beam sampling rate and thereby slightly reduce the resulting image uniformity, they are significantly more achromatic than holographic diffusers and can therefore be used with polychromatic light sources. This embodiment also provides a significant advantage over the prior art in that it does not require the intervening space and volume between the prior art lenslet arrays and thereby allows for construction of more compact systems.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention can be obtained when the following detailed description of the preferred embodiment is considered in conjunction with the following drawings.

FIGURE 1 is a diagram illustrating ellipitical and parabolic arc lamps in the prior art.

FIGURE 2 is a diagram illustrating an elliptical arc lamp and light tunnel homogenizer in the prior art.

FIGURE 3 is a diagram illustrating a lenslet array in the prior art.

FIGURE 4 is a functional block diagram of an illumination system in accordance with one embodiment of the invention.

FIGURE 5A is a diagram illustrating a lenticular array.

FIGURE 5B is a diagram illustrating a compound crossed lenticular.

FIGURE 5C is a diagram illustrating an integrated crossed lenticular

FIGURE 6 is a diagram illustrating the components of an illumination system in accordance with one embodiment of the invention.

FIGURE 7 is a set of diagrams illustrating an optical system designed to expand a light beam from a diode edge emitter laser beam optics by varying degrees in orthogonal planes.

FIGURE 8A is a diagram illustrating the profile of a cone of light emerging from a holographic diffuser in one embodiment of the invention.

FIGURE 8B is a diagram illustrating the profile of a cone of light emerging from a holographic diffuser in an alternative embodiment.

FIGURE 8C is a diagram illustrating the profiles of several cones of light emerging from a holographic diffuser in one embodiment.

FIGURE 9 is a diagram illustrating the specific design of an illumination system in a preferred embodiment.

FIGURE 10 is a flow diagram illustrating the operation of an illumination system in accordance with one embodiment of the invention.

FIGURE 11A is a diagram illustrating a prior art transmissive imager system.

FIGURE 11B is a diagram illustrating an embodiment of the present system including a transmissive imager.

FIGURE 12A is a diagram illustrating a Polarizing Beam Splitter/Imager system in the prior art.

FIGURE 12B is a diagram illustrating a Polarizing Beam Splitter/Imager system in accordance with one embodiment of the invention.

FIGURE 13A is a diagram illustrating a Prior art one color sequential imaging system.

FIGURE 13B is a diagram illustrating a color sequential imaging system in accordance with one embodiment of the invention.

FIGURE 14 is a functional block diagram of an embodiment in which multiple laser beams are combined in a single illumination source.

FIGURE 15 is a diagram illustrating the physical layout of the embodiment of FIGURE 14.

FIGURE 16 is a footprint of the two beams on the holographic diffuser in the embodiment of FIGURE 14.

FIGURE 17 is a diagram of another embodiment in which multiple laser beams are combined in a single illumination source.

FIGURE 18 is a functional block diagram illustrating one embodiment of a system configured to reduce speckle in the illumination image.

FIGURE 19 is a diagram illustrating the physical layout of the embodiment of FIGURE 18.

FIGURE 20 is a diagram illustrating the motion of a controlled angle diffuser in one embodiment corresponding to FIGURES 18 and 19.

FIGURE 21 is a diagram illustrating the motion of a controlled angle diffuser in a second embodiment corresponding to FIGURES 18 and 19.

FIGURE 22 is a functional block diagram illustrating one embodiment of a system configured to eliminate zero-order light leak in the illumination image.

FIGURE 23 is a diagram illustrating the physical layout of one embodiment of an illumination system configured to eliminate zero-order light leak.

FIGURE 24 is a diagram illustrating the physical layout of a second embodiment of an illumination system configured to eliminate zero-order light leak.

FIGURE 25 is a functional block diagram illustrating one embodiment of a system utilizing a split controlled angle diffuser.

FIGURE 26 is a diagram illustrating the physical layout of one embodiment of an illumination system utilizing a split controlled angle diffuser.

FIGURE 27A is a diagram illustrating the footprint of the beams of the controlled angle diffuser in one embodiment.

FIGURE 27B is a diagram illustrating the footprint of the beams of the controlled angle diffuser in a second embodiment.

FIGURE 28 is a diagram illustrating the diffraction of light at two points on a segmented holographic diffuser.

FIGURE 29 is a diagram illustrating the diffraction of light of different wavelengths at two points on a non-segmented holographic diffuser.

FIGURE 30 is a functional block diagram illustrating one embodiment of a system utilizing a polychromatic light beam and an achromatic diffuser.

FIGURE 31 is a diagram illustrating the physical layout of one embodiment of the system of FIGURE 30.

FIGURE 32 is a diagram illustrating the physical layout of an alternative embodiment of the system of FIGURE 30.

FIGURE 33 is a diagram illustrating the physical layout of a second alternative embodiment of the system of FIGURE 30.

FIGURE 34 is a diagram illustrating the physical layout of one embodiment of a single-gun system.

FIGURE 35 is a diagram illustrating the physical layout of a second embodiment of a single-gun system.

FIGURE 36 is a diagram illustrating a beam expander rod as used in the embodiment of FIGURE 35.

FIGURE 37 is a functional block diagram illustrating a system utilizing an image combiner to combine monochromatic images into a polychromatic image.

FIGURE 38 is a diagram illustrating the physical layout of the system of FIGURE 37.

FIGURE 39 is a diagram illustrating an alternative physical layout of the system of FIGURE 37.

FIGURE 40 is a functional block diagram illustrating a system utilizing a beam combiner between the field lenses and images of a plurality of illumination systems.

FIGURE 41 is a diagram illustrating the physical layout of the system of FIGURE 40.

FIGURE 42 is a diagram illustrating an alternative physical layout of the system of FIGURE 40.

FIGURE 43 is a functional block diagram illustrating a display system utilizing an optical processing system in accordance with the present disclosure.

FIGURE 44 is a functional block diagram illustrating one embodiment of an optical processor as used in the display system of FIGURE 43.

FIGURE 45 is a diagram illustrating the physical layout of one embodiment of an optical processor as used in the display system of FIGURE 42.

FIGURE 46 is a functional block diagram illustrating a display system utilizing a beam combiner between the optical processors and the illumination image in accordance with one embodiment.

FIGURE 47 is a functional block diagram illustrating one embodiment of an optical processor as used in the display system of FIGURE 46.

FIGURE 48 is a diagram illustrating the physical layout of one embodiment of an optical processor as used in the display system of FIGURE 46.

FIGURE 49 is a functional block diagram illustrating one embodiment of a system having a selectable illumination image.

FIGURE 50 is a diagram illustrating the physical layout of the embodiment of FIGURE 49.

FIGURE 51 is a second diagram illustrating the physical layout of the embodiment of FIGURE 49.

FIGURE 52 is a diagram illustrating one mechanism for mechanically selecting a controlled angle diffuser in one embodiment corresponding to FIGURES 49 - 51.

FIGURE 53 is a diagram illustrating a second mechanism for mechanically selecting a controlled angle diffuser in an embodiment corresponding to FIGURES 49 - 51.

DESCRIPTION OF THE PREFERRED EMBODIMENT

A preferred embodiment of the invention is described below. It should be noted that this and any other embodiments described below are exemplary and are intended to be illustrative of the invention rather than limiting.

In broad terms, the present invention comprises a system and method for processing a laser light beam in an optical system that uses a controlled angle diffuser to produce an image of predetermined shape and intensity.

Referring to FIGURE 6, a preferred embodiment of th- --vention is shown. The invention comprises a laser light source 1, a beam expansion and collimating section 2, a holographic diffuser 3, a first field lens 4, and a second field lens 5. In this embodiment, all elements are coaxially centered. The function of the optical processing by the component elements is to convert the incoming substantially collimated round Gaussian laser beam to a uniform rectangular illumination plane 6 for use in illuminating a spatial light modulator such as a liquid crystal display panel (or any other type of imager). The spatial light modulator can either be illuminated immediately following the field lens 5 or the illumination plane 6 can be optically relayed with or without magnification to another position in the system.

The laser light source in one embodiment may comprise an edge emitting laser. Typically, such a laser emits light in a pattern which has different orthogonal divergences. That is, the emitted beam diverges more in a first plane than in a second plane. The beam must therefore be corrected by an optical system (e.g., beam expander) which has a different prescription in the first plane than in the second. This may be achieved in one embodiment using a pair of crossed cylindrical lenses of different powers as the diverging lens of the beam expander. The configuration of the pair of cylindrical lenses in this embodiment is shown in FIGURE 7. Referring to FIGURE 7, it can be seen that the first cylindrical diverging lens 2c causes the beam to diverge in a first plane, but not a second. The second cylindrical diverging lens 2d, on the other hand, causes the beam to diverge in the second plane, but not the first. After the beam has passed through both of the cylindrical diverging lenses, the divergence is equal in both planes and can be collimated by a converging lens. The beam exiting the beam expander is therefore collimated in both planes.

It should be noted that the cylindrical lenses described above may be replaced in another embodiment by a single astigmatic lens which performs the same function (refracting the beam by different amounts along different axes.) Likewise, the correction of the different divergences need not be corrected by the diverging lens(es). It might instead be corrected by a pair of cylindrical converging lenses, or by other elements in the optical system. In another embodiment, the divergence of the beam from the laser light source might already have greater divergence than desired in one plane so that one of the cylindrical lenses might be a converging lens while the other is a diverging lens. Many such variations are possible.

Light Emitting Diodes may also be used as light sources in other embodiments. If an LED is used, an optical system which converts the LED output profile to a substantially collimated beam is positioned following the LED. Optical systems to accomplish this are well known in the art.

The preferred embodiment would use a high power VECSEL (Vertical Cavity Surface Emitting Laser) such as those manufactured by Novalux, Inc and termed NECSEL (Novalux Extended Cavity Surface Emitting Laser) due to its substantially cylindrical beam shape and high power capability.

The ability to modify the system to operate with a wid- --ge of sources and source intensity profiles is one of the advantages that may be provided by the present system.

Laser light 1 is shown entering the system of FIGURE 6 from the left. The light is monochromatic and collimated with a typical cylindrical beam diameter of .3 – 3 mm, although other diameters and geometries are feasible. Polychromatic sources such as tunable lasers or pre-combined monochromatic sources may also be used. While the intensity profile of the beam in the preferred embodiment is Gaussian, other intensity profiles and laser multi mode profiles will work as well.

Once a substantially collimated light beam is established a beam expander can be used to expand the beam diameter. The amount by which the beam is expanded is determined by the desired F number (as will be described below). The beam expander may be omitted if the collimated source is of sufficient diameter.

A beam expander (2) expands the light beam and re-collimates the light. In a first embodiment, the beam expander is comprised of two elements and an intervening beam expansion space. In this embodiment a first plano-cave lens 2a is used to create a conical beam divergence symmetrically centered along the optical axis. A second plano-convex lens 2b is used to halt the beam expansion and re-collimate the laser beam into a second larger diameter beam having its divergence minimized so that its rays are substantially parallel to the optical axis. This larger diameter beam is then directed onto a holographic diffuser (3).

A holographic diffuser (3) follows the beam expander. In the preferred embodiment this diffuser has the properties of converting an incident laser beam to a plurality of rectangular light cone profiles as shown in FIGURE 8C according to the hologram prescription. That is, the light exiting each differential point on the diffuser forms a rectangular cone of light. The rectangular cone of light has its horizontal and vertical orthogonal angles in the ratio of the format of the desired illumination pattern for a display device. In the preferred embodiment, the desired illumination pattern at the output is a uniformly intense rectangle of 4:3 aspect ratio to correspond to standard NTSC television format and standard XGA computer monitor format. In the specific design example shown in FIGURE 9, the corresponding angles are $\square_{Horiz} = 20$ degrees and $\square_{Vert} = 14.8$ degrees. The specific horizontal and vertical angles for the 4:3 aspect ratio system or any other format are calculated as follows:

$$\square_{Horiz} = \text{Arctan}\ (.5 \times W_{Image} \ /\ D_{diff\text{-}image})$$

$$\square_{Vert} = \text{Arctan}\ (.5 \times H_{Image} \ /\ D_{diff\text{-}image})$$

Where: $\square_{Horiz}$ = diffuser horizontal half angle divergence

$\square_{Vert}$ = diffuser vertical half angle divergence

W_{Image} = Half width of the desired Image plane 6

H_{Image} = half height of the desired Image plane 6

$D_{diff\text{-}Image}$ = Distance from diffuser to Image plane 6

Other hologram prescriptions would be used for wide format HDTV, etc.) Each of these light cones is generated from energy from a small section, or sample, of the laser beam Gaussian power profile resulting in a much higher level of uniformity in each light cone than in the original beam. In the preferred embodiment, the center ray of these cone patterns is substantially parallel to the optical axis. Each ray within a given expanding cone has a corresponding parallel ray in all of the other cones being emitted from the surface. All of these parallel rays are at the same angle relative to the central axis. Each set of parallel rays will map to a unique point on the Illumination Plane 6, as a result of the field lens 4 described below. Therefore, the angular pattern of ray divergence defines the shape of the Illumination image at plane 6. Since each point in the Illumination image will be composed of energy from all points in the incoming Gaussian beam, the uniformity of the illumination Plane is substantially improved over the uniformity of the original gaussian beam. The effect is similar to the prior art lenslet array systems whereby each rectangular cone of light is created by sampling the incoming beam at all points and then overlaying the samples on each other at the illumination plane. The Lenslet arrays sample a much lower spatial frequency and therefore produce a less uniform result.

Other light cone profiles (e.g., circular) are also feasible as shown in FIGURE 8B. In fact, the profile may be arbitrarily defined for the application.

The final uniformity is then dependent primarily on the angular power profile of the diffraction pattern of the holographic diffuser. In the preferred embodiment, this profile is that of substantially linear power per degree of solid angle to effect a near uniform power and intensity in the Illumination image. Nonlinear hologram power profiles versus angle of divergence of the light cones can be designed into the hologram to compensate for geometric uniformity problems in the illumination pattern such as the $\cos^4$ power rolloff or other system non-uniformities.

Referring to FIGURE 8A, a diagram illustrating the diffraction of light at a single point on a holographic diffuser is shown. As the collimated light passes through the holographic diffuser, it is diffracted so that it exits in a certain cone of light. ("Cone" refers to the solid angle into which the light is radiated.) The cone may be irregularly shaped, as indicated by the dashed line at the right side of the figure if other illumination plane formats are desired . This dashed line is the outline of the diffraction pattern image. The diffraction pattern image is characteristic of the holographic diffuser, and the light emanating from each point on the holographic diffuser radiates outward in a cone of the same shape (i.e., the shape of the image.)

The holographic diffuser can be configured to create any desired diffraction pattern (and corresponding image.) Referring to FIGURE 8B, a holographic diffuser configured to generate a

rectangular image from each incident point is illustrated. It is ~~~templated that a holographic diffuser which is configured to generate this type of image will be useful in applications such as projection-type displays, where a rectangular light source is desired. More particularly, the holographic diffusers which are used in display devices can be configured to produce an image which is uniformly intense across its entire area, thereby resulting in a higher-quality image on the display.

It should be noted that the dashed image outlines illustrated in FIGURES 8A and 8B are not themselves images. They are instead representative of the cross-section of the cone into which light radiates from a particular point on the holographic diffuser. Thus, light radiating from a different point on the holographic diffuser will radiate into an identical cone which is displaced laterally from the illustrated cone. While the cones originating at each point on the holographic diffuser are displaced from each other, the image which is produced by passing this light through a field lens and thereby focusing it does not move with the addition of light emanating from new points on the holographic diffuser. Instead, this additional light increases the intensity of the image which has already been formed. The additional light may, however alter the angular extent of the image formed by the lens.

FIGURE 8C shows some of the plurality of rectangular patterns generated across the hologram from the area illuminated by the laser beam.

The profile of the illumination footprint on the diffuser controls the angular extent of the light cones exiting the Illumination Plane (6) and thus the numerical aperture or F number of the system. Parallel rays from the diffuser pattern all map to a unique point on the Illumination Plane. The exit angle of that ray from the Illumination Plane 6 is determined by the radial offset of that ray from the image point. The collection of rays which pass through the image point thereby set the light cone shape and divergence corresponding to that point.

Therefore, the diffuser (3) solid cone angle shape (i.e., the diffraction pattern) defines the spatial extent of the Illumination image and the Laser Illumination footprint on the diffuser (3) defines the shape of the light cones and the F number at the Illumination Plane (6.)

In alternative embodiments, crossed lenticular lenses (FIGURE 5A and 5B) or lenslet arrays (FIGURE 5C) can be used in place of the holographic diffuser. Both of these alternatives have more achromatic performance and can be used more easily with polychromatic light sources, but they sample the source beam at a lower spatial frequency than a holographic diffuser and may therefore reduce the uniformity of the illumination image relative to the Holographic diffuser embodiment. Aspheric lenslet surfaces may be used to tailor the angular power profile and thereby further improve the Illumination image uniformity.

A first field lens (4) follows the diffuser surface. The field lens 4 maps each parallel ray from the diffuser to a unique point on an Illumination Plane 6 effectively performing and angle to area transformation on the light exiting the diffuser. This process in effect overlays each of the diffuser

rectangular cones on each other in the Illumination Plane 6 producing a highly uniform image. The Illumination Plane 6 is located one focal length from field lens (4) and, in the preferred embodiment, produces a rectangular Illumination image having a 4:3 aspect ratio. This should not, however, be considered a limitation, as other values may be viable in a given embodiment, depending on its geometry.

The physical lens may be a common single element lens or it may be a relief fresnel lens or a holographic fresnel lens. An advantage of using any of the fresnel lenses is that they are lower cost and in some cases can be laminated to the diffuser for further assembly simplicity and cost reduction.

A second field lens (5) which has the same focal length as the first field lens is placed at the image plane (6) of the first field lens. The function of this lens is to correct the divergence of the telecentric cone angles exiting the Illumination Plane. Without this lens, the centroid of each light cone bundle exiting the Illumination Plane is directed along a radial from the center of the first field lens (4.) In other words, the centroid of the light cone lies on the line extending from the center of the first field lens to the point at the image plane which defines the vertex of the cone. By adding a second field lens (5) at the Illumination Plane (6) with a focal length equal to the first field lens (4) and having sufficient diameter to circumscribe the entire Illumination Plane image, the light cones exiting the Illumination Plane can be made to have their respective centroid exit angles substantially parallel to the optical axis. This lens can be either overpowered or underpowered, that is its focal length may be adjusted as the imaging optics system requires. This geometry will provide telecentric light in plane (7) which can then be imaged onto a display device such as a reflective or transmissive LCD or similar device.

A specific design example of the preferred embodiment is shown in FIGURE 9.

A functional diagram of the preferred embodiment is shown in FIGURE 10.

The optical system described above may be used for a number of purposes. One of these purposes is the illumination of an imager in a projection display device. It is desirable in such devices to have a source of illumination which is uniform and which has a shape corresponding to the shape of the imager used in the device. In this instance, a holographic diffuser which forms such an image can be selected. The optical system can then be configured to focus this image either on a plane which is coincident with the imager of the display device, or on a plane from which it can be transmitted, via relay optics, to the imager.

Several projection system utilizing the invention are shown in FIGURES 11 and 12. These architectures are well known in the art and should be exemplary of how the invention can be used in such systems.

FIGURE 11A shows a typical prior art system using an arc lamp using three separate imagers for each primary red, green and blue color and three transmissive imagers system for each

corresponding primary. In this case optical filters are used to separate the white light from the source into its constituent primary colors.

FIGURE 11B shows a three imager transmissive system which uses three separate imagers for each primary red, green and blue color with three separate monochromatic illumination sources which each comprise the invention. In each of the separate illumination sources, the hologram prescription is designed to operate at a specific monochromatic wavelength so as to produce the same size illumination image to fit the spatial light modulator(the imager) each of which are the same size and shape. In the case of three imager systems, all sources are on continuously.

FIGURE 12A shows a typical prior art three polarizing beam splitter system using an arc lamp using three separate imagers for each primary red, green and blue color and three transmissive imagers system for each corresponding primary. In this case optical filters are used to separate the white light from the source into its constituent primary colors.

FIGURE 12B shows a three imager, three beamsplitter reflective imager system using three independent sources comprising the invention as described above.

FIGURE 13A shows a typical prior art one imager color sequential system using an arc lamp source and a color filter wheel for temporal color sequencing. The sources are temporally modulated in sequence with the color information active on the spatial light modulator(the imager.)

FIGURE 13B shows a one imager color sequential system also using three independent sources comprising the invention pre-combined by a color combiner to produce a coaxial polychromatic illumination source. The sources are temporally modulated in sequence with the color information active on the spatial light modulator(the imager.)

Another purpose for which the present system can be used is the combination of laser light beams for input to an optical fiber. Laser light sources are currently used in fiber optic communication systems to provide optical signals which are input to the fibers. Often, however, these laser light sources do not provide sufficient power to transmit signals over the desired distances.

MULTIPLE BEAMS

An alternative embodiment is described below. This embodiment comprises a system and method for combining a plurality of laser light beams in an optical system that uses a controlled angle diffuser to produce an image of predetermined shape and intensity. The generated image may be used for a variety of purposes. For example, the image may be a uniformly intense rectangle suitable for use in a display device, or it may be a round dot suitable for transmitting the light into an optical fiber.

Referring to FIGURE 14, a functional block diagram of this embodiment is shown. The laser beams which are to be combined are generated by one or more lasers 111. The beams are parallel, but are not coaxial. Typically, the beams are round and are 0.3-3 millimeters in diameter and have gaussian profiles with respect to their energy densities. Other beam geometries and profiles are possible, however. The beams are typically in close proximity to each other. The distance between the beams is dependent upon the configuration of the particular embodiment. The beams may be non-parallel as well to effect special output characteristics of size, shape and divergence, or to allow for manufacturing tolerances.

The laser light beams are passed through one or more beam expanders 112. The expanded beams are then passed through a holographic diffuser 113. Other types of controlled angle diffusers may be used. The holographic diffuser diffracts the collimated light from each of the laser beams according to the hologram prescription. In this embodiment, this diffuser pattern is an expanding rectangle of prescribed divergence whose orthogonal angles are in the ratio of the desired illumination pattern for a display device format. In this embodiment, the desired illumination pattern at the output is a uniformly intense rectangle.

The light emerging from holographic diffuser 113 is passed through a field lens 114, which performs an angle to area transformation on the diffused light and thereby produces a uniform rectangular spatial pattern one focal distance from the field lens. This can be seen in the ray traces on FIGURE 15 between elements 113 and 123. As incoming laser beam area or power is increased, the brightness of the rectangular pattern increases with no change in its uniformity, shape or size. The angular extent of the light in the image plane is a function of the spatial extent of the light leaving the diffuser. Thus, the illustrated system generates an image, which has a shape and intensity and angular distribution determined by holographic diffuser 113 at a plane determined by field lens 114.

Referring to FIGURE 15, the physical layout of this embodiment is shown. In this figure, the lasers which generate the light beams are not shown. The beams are illustrated entering the optical system from the left side of the figure. In this embodiment, the system is configured to use a separate beam expander for each of the laser light beams. Each of the beam expanders consists of a first, diverging lens 121 and a second, converging lens 122. The expanded beams are then passed through a single holographic diffuser 113 and a single field lens 114. The footprint of the two beams on holographic diffuser 113 is shown in FIGURE 16. The image generated by holographic diffuser 113

and field lens 114 lies on plane 123. It can be seen from the figure that, while the image at plane 123 may be uniform in intensity, the light cones emanating from each point (in the absence of an optical element at that point) radiate outward in a spherical pattern which is not parallel to the axis of the optical system. A second field lens 124 is therefore located at plane 123 to correct the light cones exiting the plane (i.e., to cause all of the cones of emanating light to be aligned, or telecentric with the optical axis.) SomeaApplications may require overcorrection of the telecentricity.

Referring to FIGURE 17, an alternate embodiment of a system which uses a plurality of input beams is shown. In this embodiment, the laser light beams which are input to the optical system are again parallel. This produces two expanded beams which are parallel. The footprint of the expanded beams on holographic diffuser 113 is the same as shown in FIGURE 16, and all of the light will contribute to the intensity of a single image formed by the holographic diffuser, as explained above.

The operation of the optical system described above is therefore generally as illustrated in FIGURE 17. Referring to this figure, parallel laser light beams are provided for input to the system. These beams are expanded and are then passed through a holographic diffuser. The light which emanates from the holographic diffuser is then focused to obtain the desired image on a plane at a finite distance from the focusing (field) lens.

This embodiment of the system may be used for a number of purposes. One of these purposes is the illumination of an imager in a projection display device. It is desirable in such devices to have a source of illumination which is uniform and which has a shape corresponding to the shape of the imager used in the device. In this instance, a holographic diffuser which forms such an image can be selected. The optical system can then be configured to focus this image either on a plane which is coincident with the imager of the display device, or on a plane from which it can be transmitted, via relay optics, to the imager.

Another purpose for which this system can be used is the combination of laser light beams for input to an optical fiber. Laser light sources are currently used in fiber optic communication systems to provide optical signals which are input to the fibers. Often, however, these laser light sources do not provide sufficient power to transmit signals over the desired distances. Using the present system, a plurality of laser light beams can be combined for input to a single fiber. In this instance, a diffuser which images the light beams as a single spot smaller than the diameter of the fiber can be selected. The spot can be imaged onto the end of the fiber, thereby transmitting the light into the fiber. In this embodiment, the aperture of the diffuser and/or corresponding field lens can be selected to ensure that the light which is imaged onto the optical fiber is within the numerical aperture necessary to transmit the light into the fiber.

SPECKLE REDUCTION

Another alternative embodiment is described below. This embodiment comprises a system and method for processing one or more laser light beams in an optical system that uses a movable controlled angle diffuser to produce an image of predetermined shape and intensity without speckling. The generated image may be used for a variety of purposes. For example, the image may be a uniformly intense rectangle suitable for use in a display device, or it may be a dot suitable for transmitting the light into an optical fiber.

Referring to FIGURE 18, a functional block diagram of this embodiment is shown. The laser beam is generated by laser 211. The beam is typically .3-3 millimeters in diameter and has a gaussian profile with respect to its energy density. Other geometries and profiles are possible, however.

The laser light beam is passed through a beam expander 212. The expanded beam is then passed through a holographic diffuser 213, although other types of controlled angle diffusers may be used. In this embodiment, the diffuser pattern is an expanding rectangle of prescribed divergence whose orthogonal angles are in the ratio of the desired illumination pattern for a display device format.

The light emerging from holographic diffuser 213 is passed through a field lens 214, which performs an angle to area transformation on the diffused light. This can be seen in the ray traces on FIGURE 19 between elements 213 and 223. Thus, the illustrated system generates an image which has a shape, intensity, and angular distribution determined by holographic diffuser 213 at a plane determined by field lens 214.

In this embodiment, the holographic diffuser is continually moved. The effectively "smears" the speckling over the image. The diffuser may be moved in a number of ways such as a reciprocating motion or a circular motion. Because the light exiting the diffuser at any point is the same, the movement will not affect the image as long as the axis orientation of the diffuser remains the same.

Referring to FIGURE 19, the physical layout of this embodiment is shown. In this figure, the laser which generates the light beam is not shown. The beam is illustrated entering the optical system from the left side of the figure. In this embodiment, the system is configured to use a beam expander to increase the diameter of the laser light beam. The beam expander consists of a first, diverging lens 221 and a second, converging lens 222. The expanded beam is then passed through a holographic diffuser 213 and a field lens 214. The image generated by holographic diffuser 213 and field lens 214 lies on plane 223. A second field lens 224 is located at plane 223 to correct the rays exiting the plane (i.e., to cause all of the cones of emanating light to be aligned, or telecentric with the optical axis.) Some applications may require over-correction of the telecentricity.

It is characteristic of laser light that images produced by a stationary diffracting element using this light are speckled. This is a result of the fact that the laser light is coherent and

monochromatic. The net effect is often a high frequency mottling of the image formed by the laser light, sometimes called "worminess." This effect can be reduced if the holographic diffuser is continually moved as indicated in FIGURES 20 and 21. The movement of the diffuser effectively smears or blurs the speckling. The diffuser need not move in a particular direction (e.g., in a reciprocating or circular motion), but the axis orientation of the diffuser should remain the same despite the motion. In other words, the diffuser should be displaced by the motion, but the motion should not change the optical axis orientation in which the diffuser faces. (It should be noted that, while it is not contemplated that circularly symmetric images are not likely to be used, such an image would permit the present system to be implemented by rotating the diffuser.)

As indicated in FIGURE 19, the holographic diffuser is coupled to a piezoelectric device in one embodiment. The piezoelectric device is configured to move the diffuser in response to an electrical signal. When the signal is high, the piezoelectric device moves the diffuser toward a first position, and when the signal is low, the device moves the diffuser toward a second position. Thus, a signal which alternates between high and low values (e.g., a sine wave) causes the piezoelectric device to move the diffuser back and forth. See FIGURE 20. The amount and speed of the displacement are dependent upon the particular embodiment in which in the device is used, but should be chosen so that the movement of the holographic diffuser is sufficient to reduce the speckling effect. In other embodiments, other types of motion may be employed (see, e.g., FIGURE 21,) and corresponding means for imparting this motion to the diffuser will be necessary.

Referring to FIGURES 20-21, it is contemplated that a holographic diffuser which is configured to generate a uniformly intense, rectangular image will be useful in applications such as projection-type displays, where a rectangular light source is desired. More particularly, the holographic diffusers which are used in display devices can be configured to produce an image which is uniformly intense across its entire area, thereby resulting in a higher-quality image on the display. The quality of the image (and more specifically, the uniformity of the image) is improved by reducing the effect of laser speckle.

ZERO-ORDER LIGHT-LEAK ELIMINATION

Another alternative embodiment is described below. This embodiment comprises a system and method for processing one or more laser light beams in an optical system that uses a controlled angle diffuser to produce an image which is displaced from a zero-order light leak. The generated image may be used for a variety of purposes. For example, the image may be a uniformly intense rectangle suitable for use in a display device.

The system uses a controlled angle diffuser such as a hologram, or bulk scatterer which can be designed to transmit or reflect incident light in a diffraction pattern angularly in a predetermined geometry. In order to eliminate the "zero-order leak," or that portion of the incident energy which is

unaffected by the diffraction pattern of the hologram and continues to propagate along the direction of incidence, certain hologram prescriptions and component configurations are required.

One solution is to use a hologram prescription whose input wavefront is designed to be angularly displaced from the perpendicular axis of the hologram by an angle greater than the maximum angle generated by the hologram diffraction pattern, but has its output diffraction pattern designed to propagate symmetrically along the perpendicular axis of the diffuser. This has the effect of forcing the angle of the zero order leak to be greater than the maximum angle set of the diffraction pattern prescription. It is thereby geometrically separated from the intended diffraction energy and can be isolated and discarded.

An alternate configuration is to use a hologram prescription whose input wavefront is along the perpendicular axis of the hologram, but whose output diffraction pattern is designed to propagate at an angle from the perpendicular axis of the diffuser which is greater than the maximum angle generated by the hologram diffraction pattern. This also has the effect of forcing the angle of the Zero Order Leak to be greater than the maximum angle set of the diffuser diffraction pattern prescription. It is thereby geometrically separated from the intended diffraction energy and can be isolated and discarded.

Referring to FIGURE 22, a functional block diagram of this embodiment is shown. The laser beam is generated by laser 311. The laser light beam is passed through a beam expander 312. The expanded beam is then passed through a holographic diffuser 313, which diffracts the collimated light according to the hologram prescription. (Other types of controlled angle diffusers may be used.)

The light emerging from holographic diffuser 313 is passed through a field lens 314, which performs an angle to area transformation on the diffused light. A diffuser which produces a rectangle in angle space(an expanding rectangle) will produce a rectangular spatial pattern one focal distance from the field lens. This can be seen in the ray traces on FIGURE 23 between elements 313 and 323. Thus, the illustrated system generates an image which has a shape, intensity, and angular distribution determined by holographic diffuser 313 at a plane determined by field lens 314.

Referring to FIGURE 23, the physical layout of this embodiment of the present system is shown. In this figure, the laser which generates the light beam is not shown. The beam is illustrated entering the optical system from the left side of the figure. In this embodiment, the system is configured to use a beam expander to increase the diameter of the laser light beam. The beam expander consists of a first, diverging lens 321 and a second, converging lens 322. The expanded beam is then passed through a holographic diffuser 313 and a field lens 314. The image generated by holographic diffuser 13 and field lens 314 lies on plane 323. It can be seen from the figure that, while the image at plane 323 may be uniform, the light cones emanating from each point radiate outward in a spherical pattern which is not parallel to the axis of the optical system. A second field lens 324 is therefore located at plane 323 to correct the rays exiting the plane (i.e., to cause all of the cones of

emanating light to be aligned, or telecentric.) Some applicatior~ ~ay require over-correction of the telecentricity.

It can be seen in FIGURE 23 that holographic diffuser 313 and field lens 314 are angled with respect to the incident light beam and lenses 321 and 322 of the beam expander, which lie along the first optical axis 331. The diffuser 313 and field lens 314 lie on a second optical axis 332. Second field lens 323 also lies on the second optical axis 332. Optical axes 331 and 332 form an angle indicated by the letter A in the figure. Angle A should be sufficiently large that the image of the zero-order light leak is outside the boundaries of the image of the diffraction pattern formed at plane 323. This requires that the angle A be greater (preferably 1-2 degrees) than the maximum diffuser pattern half angle in the direction of the angle A axis.

Referring to FIGURE 24, the physical layout of an alternative embodiment of the present system is shown. In this embodiment, the laser light beam is again expanded and transmitted to a holographic diffuser 313. In this instance, holographic diffuser 313 is not configured to diffract the transmitted light along its own optical axis (which in this case is coincident with the axis of the incident light.) Instead, diffuser 313 is configured to diffract the radiated light off-axis. Thus, although holographic diffuser 313 and field lens 314 are aligned with the incident light beam, the image formed by the beam is displaced from optical axis 331 by an angle A (in assuming that the same amount of displacement as in FIGURE 23 is necessary.)

SPLIT DIFFUSER

Another alternative embodiment is described below. This embodiment comprises a system and method for combining a plurality of laser light beams of different wavelengths in an optical system that uses a segmented controlled angle diffuser to produce an image of predetermined shape and intensity. The generated image may be used for a variety of purposes. For example, the image may be a uniformly intense rectangle suitable for use in a display device.

Referring to FIGURE 25, a functional block diagram of this embodiment is shown. The laser beams which are to be combined are generated by one or more lasers 411. The beams are generally parallel, but are not coaxial. Various angles of incidence of the beams may also be used to correct for other optical problems, such as the zero order light leak characteristic of diffractive optics. Typically, the beams are .3-3 millimeters in diameter and have gaussian profiles with respect to their energy densities. Other geometries and profiles are possible, however. The beams are typically in close proximity to each other. The distance between the beams is dependent upon the configuration of the particular embodiment.

The laser light beams are passed through one or more beam expanders 412. The expanded beams are then passed through a holographic diffuser 413, which causes the light incident at each

point to radiate outward into a predetermined angular area according to the hologram prescription at the point of incidence.

The hologram prescription of diffuser 413 varies, depending upon which part of the diffuser the light strikes. More specifically, diffuser 413 comprises a plurality of segments, each of which is configured to diffract light of a particular wavelength into a specific pattern. Diffuser 413 is configured so that the resulting pattern for each segment is identical when the corresponding wavelength light is diffracted. In the preferred embodiment, this diffuser pattern is an expanding rectangle of prescribed divergence whose orthogonal angles are in the ratio of the desired illumination pattern for a display device format.

The light emerging from holographic diffuser 413 is passed through a field lens 414, which performs an angle to area transformation on the diffused light. Therefore, a diffuser which produces a rectangle in angle space(an expanding rectangle) will produce a rectangular spatial pattern one focal distance from the field lens. This can be seen in the ray traces on FIGURE 26 between elements 413 and 424. Thus, the illustrated system generates overlapping monochromatic images (at a plane determined by field lens 414 and field lens 424) which have a shape and intensity determined by holographic diffuser 413.

Referring to FIGURE 26, the physical layout of one such embodiment is shown. In this figure, the lasers which generate the light beams are not shown. It should also be noted that only two beams are shown in this figure for clarity. While the system may be used to combine two, or any other number of beams, the description of the system herein is directed primarily to embodiments in which red, green and blue beams are combined to form a white-light image.

The beams are illustrated entering the optical system from the left side of the figure. Each of the beams passes through a beam expander. Each of the beam expanders consists of a first, diverging lens 421 and a second, converging lens 422. The expanded beams are then passed through a segmented holographic diffuser 413 and a single field lens 14, which focuses the respective beams at plane 423.

The footprint of the beams on holographic diffuser 413 in one embodiment is shown in FIGURE 27A. In this embodiment, three beams are input to the system. (The footprint of an embodiment in which six beams are combined is shown in FIGURE 27B.) It can be seen in this figure that each of the beams is incident on a separate segment of diffuser 413. The segments are indicated by the reference numerals 415a, 415b and 415c. Each of these segments is configured to operate with a particular wavelength of light and each is configured to generate essentially the same diffraction pattern for its respective wavelength. (It should be noted that, because the field lens likely has a slightly different focal length for each of these wavelengths, the diffuser segments may be configured to emit the different wavelengths into slightly different angular areas to compensate for the

aberration.) After the different light beams pass through their respective segments of diffuser 413, they are focused by field lens 414 into the identical image (albeit in different colors.)

The image generated by holographic diffuser 413 and field lens 414 lies on plane 423. It can be seen from the figure that, while the image at plane 423 may be uniform in intensity, the light cones emanating from each point (in the absence of an optical element at that point) radiate outward in a spherical pattern which is not parallel to the axis of the optical system. A second field lens 424 is therefore located at plane 423 to correct the light cones exiting the plane (i.e., to cause all of the cones of emanating light to be aligned, or telecentric with the optical axis.) Some applications may require overcorrection of the telecentricity.

Referring to FIGURE 28, a diagram illustrating the diffraction of light at two points on a segmented holographic diffuser is shown. As the collimated light passes through the holographic diffuser, it is diffracted so that it exits in a certain cone of light. The cone is shown here being rectangular. The diffraction pattern image is characteristic of the segment of the holographic diffuser through which the light passes. Monochromatic light emanating from each point within a segment of the holographic diffuser radiates outward in a cone of the same shape (i.e., the shape of the image.)

FIGURE 28 shows an upper segment 415a and a lower segment 415b. Two rays are shown hitting diffuser 413 – one striking segment 415a and one striking segment 415b. It is assumed that the ray hitting segment 415a has a wavelength corresponding to this segment of the diffuser. Likewise, the ray hitting segment 415b has a wavelength corresponding to that segment. As a result of the matching of the appropriate rays and diffuser segments, light emanates outward from each point into essentially identical solid angles, each being displaced by the spacing of the beams. Because the light rays radiate into the same solid angle, the focusing of these rays will form overlapping images. If the diffuser were not segmented, the light from the each of the rays would radiate outward into different solid angles as shown in FIGURE 29. In this instance, the resulting image would not be as uniformly illuminated.

POLYCHROMATIC BEAM WITH ACHROMATIC DIFFUSER

Another alternative embodiment is described below. This embodiment comprises a system and method for combining a plurality of laser light beams of different wavelengths in an optical system that uses an achromatic controlled angle diffuser to produce a white light image of predetermined shape and intensity. The generated image may be used for a variety of purposes, such as a source of illumination in a display device.

It should be noted that "achromatic" is used here to refer to diffusers which identically (or nearly identically) diffract the particular wavelengths used in the system. They may be limited in their achromatic performance and behave achromatically for a limited subset of wavelengths which are those particular wavelengths of the lasers used in that particular system. The diffuser may behave

in a manner which is not achromatic for wavelengths which ar~ ~~t used in the system, but this obviously will not affect the system.

Referring to FIGURE 30, a functional block diagram of this embodiment is shown. The laser beams which are to be combined are generated by one or more lasers 511. The beams may initially be in a variety of configurations. The beams are combined by beam combiner 510, after which they are parallel and preferably coaxial. ("Combined" as used here is not intended to imply that the beams are necessarily overlapped, but simply that they are parallel and positioned for input to the optical processing system.) Typically, the beams are .3-3 millimeters in diameter and have gaussian profiles with respect to their energy densities, although other geometries and profiles are possible.

The laser light beams are passed through one or more beam expanders 512. The expanded beams are then passed through an achromatic holographic diffuser 513. The achromatic holographic diffuser 513 diffracts the collimated light from each of the laser beams according to the hologram prescription. Because the holographic diffuser is achromatic, the diffraction pattern is the same for any color of light. In some embodiments, types of controlled angle diffusers other than holographic diffusers may be used.

The light emerging from holographic diffuser 513 is passed through a field lens 514, which performs an angle to area transformation on the diffused light. Therefore, a diffuser which produces a rectangle in angle space(an expanding rectangle) will produce a rectangular spatial pattern one focal distance from the field lens. This can be seen in the ray traces on FIGURE 31 between elements 513 and 523. Thus, the illustrated system generates an image, which has a shape and intensity and angular distribution determined by holographic diffuser 513 at a plane determined by field lens 514.

Referring to FIGURE 31, the physical layout of one embodiment of the present system is shown. In the system depicted this figure, three laser sources (511a-511c) are employed to generate light beams of three different colors. A beam generated by a first one of the laser sources 11a is aligned with the optical axis of the beam expander. This is also the axis of combiner 510, which comprises two beam splitters (dichroic filters) 526a and 526b. Each of the beam splitters lies in the optical path of the beam generated by laser sources 11a. Each of the beam splitters is also aligned with one of the other laser sources (511b and 511c.) The beam splitters are configured to reflect the light beams from the respective laser sources so that the beams will be reflected along the optical axis of the combiner 510 and beam expander 512. Beam splitters 526a and 526b are each configured to reflect light having a particular wavelength and to transmit all other wavelengths. More specifically, they are configured to reflect light having the same wavelength as the respective laser sources. Thus, the light generated by laser source 511a passes through both beam splitters and is incident on lens 521. Similarly, the light generated by laser source 511b is reflected off of beam splitter 526a and passes through beam splitter 526b. The light generated by laser source 511c is reflected off of beam splitter 526b and into the beam expander.

In this embodiment, the beams are combined coaxially ~ nearly so. Consequently, the system is configured to use a single beam expander for the combined laser light beams. The beam expander consists of a first, diverging lens 521 and a second, converging lens 522. The expanded beams are then passed through achromatic holographic diffuser 513 and a single field lens 514. The image generated by holographic diffuser 513 and field lens 514 lies on plane 523. A second field lens 524 is located at plane 523 to correct the ray angles exiting the plane. Some applications may require overcorrection of the telecentricity.

Referring to FIGURE 32, a second embodiment of the present system is shown. In this embodiment, the laser light sources are arranged so that the second and third beams (from sources 511b and 511c) are combined from opposite sides of the optical axis. Functionally, this arrangement does not differ from the embodiment of FIGURE 31. This configuration may, however, provide for a more compact package if the laser sources are large enough that they cannot be conveniently located next to each other.

Referring to FIGURE 33, a third embodiment of the present system is shown. In this embodiment, the laser light sources are arranged so that the three beams are combined by a dichroic "X" cube, an optical element known to the projection and optics industry. Functionally, this does not differ from the embodiment of FIGURE 31. This configuration provides for a more compact design of the combiner as the beam splitters occupy the half the space when they are crossed.

SINGLE-GUN DESIGN

Another alternative embodiment is described below. This embodiment comprises a device for producing an illumination source which uses multiple laser light sources and corrects for zero-order light leakage which results from the diffraction of the light. In one embodiment, the device comprises a plurality of laser light sources, wherein a plurality of collimated light beams are combined by an optical system and diffracted by a controlled angle diffuser, and wherein the system is configured to eliminate zero-order light leak. The plurality of laser light sources are positioned to generate parallel laser light beams. A heat sink is attached to the back of the device adjacent to the laser light sources. These beams are passed through a set of corresponding lenses which serve to expand each beam. Each of the expanded beams is then passed through a controlled angle diffuser which diffracts the beams and a field lens which subsequently focuses the diffraction pattern onto an image plane. The diffuser and field lens are angled to prevent zero-order leakage of light through the diffuser. The plurality of laser light sources and lenses and the diffuser are packaged in a single housing which increases in the ease of manufacture of the device.

Referring to FIGURE 34, a preferred embodiment of the present device is shown. In this embodiment, four laser light sources 641 are secured to a baseplate 642. This baseplate holds the laser light sources in position so that the light emitted from each of the sources is parallel. The

baseplate 642 also provides a convenient means for coupling a heat sink 643 to laser light sources 641 to dissipate heat generated by the sources.

The baseplate 642 is secured to a housing 645 which surrounds the components of the device and provides a means to secure them to each other. A first lens array 646 is coupled to housing 645 in front of laser light sources 641. First lens array 646 incorporates a plurality of diverging lenses 647, each of which is positioned in front of what a corresponding laser light source 641. Diverging lenses 647 are in the optical path of the laser light sources in consequently diverge the corresponding laser light beams. Each of these beams continues to diverge until it is incident upon one of a plurality of converging lenses 648. Converging lenses 648 comprise part of a second lens array 649 which is secured to housing 645. After the laser light from each of the laser light sources passes through one of the converging lenses, the light is collimated, but has a larger beam diameter than the original beam emanating from the laser light source.

Each of the expanded, collimated beams is then incident upon a controlled angle diffuser 650 which is positioned following the second lens array 649. In this embodiment, controlled angle diffuser 650 is a holographic optical element. When the laser light passes through diffuser 650, it is diffracted and forms a diffraction pattern. A field lens 651 is positioned following diffuser 650. Field lens 651 focuses the light exiting diffuser 650 onto a plane which lies one focal length in front of the lens.

The device illustrated in FIGURE 34 has several advantages over prior art illumination devices. These advantages may include increased power and improved uniformity of illumination. More particularly, the device is more powerful than other laser based illumination sources because it combines the power of a plurality of lasers in a single illumination source. The light produced by each of the lasers is combined by diffracting each laser beam to form identical diffraction patterns, then focusing the diffracted light into a single image. Each laser forms an identical image which contributes to the intensity of the image produced by the device. This image can then be formed directly on or relayed to an imager and used to generate a screen image for a display. This device also has the advantage of eliminating zero-order light leakage which may degrade the uniformity of the image produced by the diffuser. The device generates the image in a position which is off-axis from the laser light beams and thereby displaces the zero-order light leakage from the image. As a result, no correction of the image is necessary to eliminate non-uniformities resulting from the zero-order light leakage.

Referring to FIGURE 35, a second embodiment of the present device is shown. In this embodiment, the individual lenses of the beam expanders are replaced by a single lens 653. Lens 653 is actually a rod which has a first powered surface 654 on a first end and a second powered surface 655 on a second end. In this example, lens 654 is concave and lens 655 is convex. Lens 653 is shown apart from the device in FIGURE 36. Collimated light is input to the first end of the lens and exits the

second end. As the light passes through concave surface 654, the beam diverges in the same manner as it would after passing through diverging lens 647 in the embodiment of FIGURE 34. When the light reaches convex surface 655, the light is recollimated in the same manner as it would be after passing through converging lens 648 in the embodiment of FIGURE 34.

The use of a beam expander such as lens 653 may provide several advantages. For example, this type of beam expander may be more efficient. Light losses in optical systems occur primarily where the light encounters a refractive surface. By using a single lens rather than two lenses, two surfaces are eliminated and the transmission efficiency of the beam expander is consequently improved. Another advantage may be found in the ease of manufacturing the device using this type of beam expander. Because the expander comprises a single lens, it is easy to control the manufacturing tolerances for the beam expander. Put another way, there is no need to maintain the alignment of two separate lenses within the housing of the device. The housing may be manufactured so that the beam expander rods can simply be dropped into position in front of the laser light sources.

IMAGE COMBINER

Another alternative embodiment is described below. This embodiment comprises a system and method for processing a plurality of laser light beams of different wavelengths using monochromatic controlled angle diffusers and then combining the processed beams to produce a white light source of predetermined shape and intensity. The generated light may be used for a variety of purposes, such as a source of illumination in a display device.

Referring to FIGURE 37, a functional block diagram of one embodiment of the present system is shown. The system comprises a plurality of optical processors 719, the output of which are directed into a beam combiner 710. Each optical processor 719 comprises a laser 711 which generates a beam of coherent, organized monochromatic light. The laser light beam is passed through a beam expander 712. The beam expander increases the diameter of the beam, but does not significantly alter the collimation of the light. The expanded beam is then passed through a monochromatic holographic diffuser 713. Holographic diffuser 713 causes a diffraction pattern to be generated by the light from the expanded laser beam.

The light emerging from holographic diffuser 713 is passed through a field lens 714, which causes an image to be formed at a distance from the lens which is equal to its focal length. Thus, the illustrated system generates an image which has a shape and intensity determined by holographic diffuser 713 at a plane determined by field lens 714. A second field lens 715 is placed at the image plane to correct the angle at which the light radiates outward from the image.

Referring to FIGURE 38, the physical layout of one embodiment of the present system is shown. In the system depicted this figure, three optical processors (719a-719c) are employed to generate light beams of three different colors. The optical processors are identical, except that each

produces an image comprising a different wavelength of light. A beam generated by a first one of the laser sources 711a is aligned with the optical axis of the corresponding beam expander 712. In this embodiment, combiner 710 and subsequent relay optics are aligned with this optical axis. The expanded beam which emerges from beam expander 712 passes through holographic diffuser 713 and is diffracted. The diffracted light is collected by field lens 714 and focused onto image plane 723. A second field lens 724 is positioned at plane 723 to correct the light emerging from image plane 723. That is, the lens ensures that the cones of light exiting the image plane are all oriented in a particular, desired direction.

Combiner 710 comprises a prism having two beam splitters (thin film interference filters,) 726a and 726b, each of which is configured so that it reflects a particular wavelength of light and passes other wavelengths. (It should be noted that various different types of wavelength separating filters are known and may be used in place of the thin film interference filters of this embodiment.) In the illustrated embodiment, filter 726a is configured to reflect the light generated by optical processor 719b and pass the light of optical processors 719a and 719c, while filter 726b is configured to reflect the light generated by optical processor 719c and the pass the light of optical processors 719a and 719b. Thus, the light which emerges from combiner 710 appears as if it were generated by a single white-light image at plane 723. This light can then be transmitted by additional relay optics to a display imager.

Referring to FIGURE 39, a second embodiment of the present system is shown. In this embodiment, the laser light sources are arranged so that the output of the second and third optical processors is combined with the output of the first optical processor using thin film interference filters which are displaced from each other along the optical axis of the first optical processor. Functionally, this arrangement does not differ from the embodiment of FIGURE 38. The configuration of the combiner used in this embodiment may, however, be more easy to manufacture than the previously described configuration.

BEAM COMBINER BETWEEN FIELD LENS AND IMAGE

Another alternative embodiment is described below. This embodiment comprises a system and method for processing a plurality of laser light beams of different wavelengths using monochromatic controlled angle diffusers and then combining the processed beams to produce a white light source of predetermined shape and intensity. The generated light may be used for a variety of purposes, such as a source of illumination in a display device.

Referring to FIGURE 40, a functional block diagram of this embodiment is shown. The system comprises a plurality of optical processors 819, the output of which are directed into a beam combiner 810. Each optical processor 819 comprises a laser 811 which generates a beam of coherent, monochromatic light. The laser light beam is passed through a beam expander 812. The expanded

beam is then passed through a monochromatic holographic dif‑‑‑‑r 813. Holographic diffuser 813 causes a diffraction pattern to be generated by the light from the expanded laser beam.

The light emerging from holographic diffuser 813 is passed through a field lens 814, which causes an image to be formed at a distance from the lens which is equal to its focal length. In this embodiment, a combiner is placed between field lens 814 and the image. As a result, the images created by each of the optical processors is focused onto the same plane, forming a single, polychromatic image. A second field lens 815 can then be placed at the image plane to correct the angle, or telecentricity with which the polychromatic light radiates outward from the image.

Referring to FIGURE 41, the physical layout of one embodiment of the present system is shown. In the system depicted this figure, three optical processors (819a-819c) are employed to generate light beams of three different colors. The optical processors are identical, except that each produces an image comprising a different wavelength of light. A beam generated by a first one of the laser sources 811a is aligned with the optical axis of the corresponding beam expander 812. In this embodiment, combiner 810 and subsequent relay optics are aligned with this optical axis. The expanded beam which emerges from beam expander 812 passes through holographic diffuser 813 and is diffracted. The diffracted light is collected by field lens 814 and focused onto image plane 823. A second field lens 824 is positioned at plane 823 to correct the light emerging from image plane 823. That is, the lens ensures that the cones of light exiting the image plane are all oriented in a particular desired direction.

Combiner 810 comprises a prism having two beam splitters (e.g., thin film interference filters,) 826a and 826b, each of which is configured so that it reflects a particular wavelength of light and passes other wavelengths. (It should be noted that various different types of wavelength separating filters are known and may be used in place of the thin film interference filters of this embodiment.) In the illustrated embodiment, filter 826a is configured to reflect the light generated by optical processor 819b and pass the light generated by optical processors 819a and 819c, while filter 826b is configured to reflect the light generated by optical processor 819c and pass the light generated by optical processors 819a and 819b. Thus, the light which emerges from combiner 810 converges at plane 823 to form a single polychromatic image. This image can be corrected by a second field lens 824 to ensure that the light cones emanating from each point on the image radiate outward in the desired direction. Usually this direction is designed to be telecentric, but others may be desirable from a system standpoint. This light can then be transmitted by the relay optics to a display imager.

Referring to FIGURE 42, a second embodiment of the present system is shown. In this embodiment, the laser light sources are arranged so that the output of the second and third optical processors is combined with the output of the first optical processor using thin film interference filters which are displaced from each other along the optical axis of the first optical processor. Functionally, this arrangement does not differ from the embodiment of FIGURE 41. The configuration of the

combiner used in this embodiment may, however, be more easy to manufacture than the previously described configuration from a mechanical assembly standpoint and the filters may be less expensive to manufacture.

DISPLAY SYSTEM

Another alternative embodiment is described below. This embodiment comprises a system and method for processing a laser light beam using a monochromatic controlled angle diffuser to produce a light source of predetermined shape and intensity. The generated light illuminates an imager, which generates an image that is conveyed via display optics to a screen for presentation to a user.

Referring to FIGURE 43, a functional block diagram of this embodiment is shown. The system comprises an optical processor 919, the output of which is directed through a beam splitter 927. The illumination image formed by the combined beams lies on a focal plane. The focal plane is sufficiently distant from the optical processor that beam splitter 927 can be positioned between the optical processor and the focal plane. An imager 928 is positioned so that it is illuminated by the image formed at the focal plane. Imager 928 may be of any suitable type, such as an LCOS (liquid crystal on silicon), DLP (micro-mirror) imager, Reflective Poly Silicon, or other reflective display of the type found in current projection displays. Light reflected from imager 928, the information image, passes back through beam splitter 927. Beam splitter 927 selectively reflects the information image to the imaging optics system 929. From there, the light is transmitted to display screen 930, where the image from the imager can be viewed by a user.

Referring to FIGURE 44, one embodiment of optical processor 919 is shown. Optical processor 919 comprises a laser light source 911 which generates a beam of coherent, monochromatic light. The laser light beam is passed through a beam expander 912, which comprises a diverging lens 921 and a converging lens 922. The expanded beam is then passed through a monochromatic holographic diffuser 913, which causes a diffraction pattern to be generated by the light from the expanded laser beam. The light emerging from holographic diffuser 913 is collected by field lens 914, which focuses the diffraction pattern into an image. This illumination image is located at a focal plane which is displaced from the field lens by its focal length. The illumination image is configured to provide illumination for the display imager (e.g., a uniformly intense rectangle having the same aspect ratio as the imager). (It should be noted that in one embodiment the light beam is monochromatic and the diffuser is designed for the corresponding wavelength, while in another embodiment the light beam is polychromatic and the diffuser is achromatic).

Referring to FIGURE 45, the physical layout of one embodiment of the system is shown. A beam generated by a laser source 911 is expanded by beam expander 912. Beam expander 912 comprises a diverging lens 921 and a converging lens 922. The expanded beam which emerges from

beam expander 912 passes through holographic diffuser 913 ar^d ^is diffracted. The diffracted light is collected by field lens 914. The light is focused by field lens 914 at image plane 923. Thus, the illustrated system generates an illumination image which has a shape and intensity determined by holographic diffuser 913 at a plane determined by field lens 914. Beam splitter 927 is positioned between field lens 914 and illumination image plane 923 so that the light passes through the beam splitter before being focused on the illumination image plane 923.

In the embodiment illustrated by FIGURE 45, a second field lens 924 is located immediately following plane 923 to correct the telecentricity of the light emerging from the illumination image to a desired level. The image produced at plane 923 is used to illuminate an imager 928. It is therefore desirable to have a uniformly intense image with an aspect ratio that matches the aspect ratio of the imager. This is easily achieved by the selection of the appropriate holographic diffuser (i.e., one that has the corresponding characteristic diffraction pattern.) Imager 928 generates an information image from this illumination. The information image is transmitted back through second field lens 924 for further correction of the telecentricity and into beam splitter 927. A portion of the information image is reflected by beam splitter 927 through display optics 929 and onto display screen 930 for viewing.

DISPLAY SYSTEM USING A BEAM COMBINER AND BEAM SPLITTER

Another alternative embodiment is described below. This embodiment comprises a system and method for processing a plurality of laser light beams of different wavelengths using monochromatic controlled angle diffusers and then combining the processed beams to produce a white light source of predetermined shape and intensity. The generated light illuminates an imager, which creates a display image for presentation to a user.

Referring to FIGURE 46, a functional block diagram of one embodiment of the present system is shown. The system comprises a plurality of optical processors 1019, the output of which are directed into a beam combiner 1010. Each of the optical processors 1019 includes a laser light source and is configured to generate a beam which is focused into an identical image. The combined beams form an illumination image which is polychromatic.

The illumination image formed by the combined beams lies on a plane 1023. Plane 1023 is sufficiently distant from the optical processors that combiner 1010, as well as a beam splitter 1027 can be positioned between the optical processors and plane 1023. A field lens 1024 is located at plane 1023 to correct the light emerging from the illumination image. This light is then incident on an imager 1028. Light reflected from imager 1028 passes back through field lens 1024 and beam splitter 1027 and is selectively reflected through a display imaging optics system 1029 and onto display screen 1030, where the image from the imager can be viewed by a user.

Referring to FIGURE 47, each optical processor 1019 comprises a laser 1011 which generates a beam of coherent, monochromatic light. The laser light beam is passed through a beam expander

1012. The expanded beam is then passed through a monochromatic holographic diffuser 1013. Holographic diffuser 1013 causes a diffraction pattern to be generated by the light from the expanded laser beam. The light emerging from holographic diffuser 1013 is passed through a field lens 1014, which causes an image to be formed at a distance from the lens which is equal to its focal length.

Referring to FIGURE 48, the physical layout of one embodiment of optical processor 1019 is shown. The optical processors 1019 are identical, except that each produces an image comprising a different wavelength of light. A beam generated by a laser source 1011 is aligned with the optical axis of the beam expander 1012. The expanded beam which emerges from beam expander 1012 passes through holographic diffuser 1013 and is diffracted. The diffracted light is collected by field lens 1014 and focused onto image plane 1023.

Referring again to FIGURE 46, combiner 1010 comprises a prism having two crossed beam splitters (thin film interference filters,) 1026a and 1026b, each of which is configured so that it reflects a particular wavelength of light and passes other wavelengths. Other combiners may be constructed using plate beamsplitters as well. In the illustrated embodiment, filter 1026a is configured to reflect the light generated by optical processor 1019a while passing light generated by optical processors 1019b and 1019c. Filter 1026b is configured to reflect the light generated by optical processor 1019c while passing light from optical processors 1019a and 1019b. Thus, white light beam emerges from the combiner 1010 and then passes through a second beam splitter 1027. The light which emerges from beamsplitter 1027 converges at plane 1023 to form a single polychromatic illumination image. This image can be corrected by a second field lens 1024 to ensure that the light emanating from each point on the image radiates outward in a particular prescribed direction toward the display imager 1028. Light reflected from the display imager 1028 is passed back through the second field lens 1024 for further correction and processing. The light is then selectively reflected by the beamsplitter 1027 to the display imaging optics 1029 and on to the display screen 1030.

SELECTABLE ILLUMINATION IMAGE

Another alternative embodiment is described below. This embodiment comprises a system and method for processing one or more laser light beams in an optical system that uses a switchable controlled angle diffuser to produce a selectable illumination image of predetermined shape and intensity.

Referring to FIGURE 49, a functional block diagram of one embodiment of the present system is shown. The laser beam is generated by laser 1111. The laser light beam is passed through one or more beam expanders 1112. The expanded beam is then passed through a holographic diffuser 1113, which diffracts the light according to the hologram prescription. The light emerging from holographic diffuser 1113 is passed through a field lens 1114, which performs an angle to area transformation on the diffused light. This can be seen in the ray traces on FIGURE 50 between

elements 1113 and 1123. Thus, the illustrated system generates an image, which has a shape, intensity and angular distribution determined by holographic diffuser 1113 at a plane determined by field lens 1114.

Referring to FIGURE 50, the physical layout of one embodiment of the present system is shown. In this figure, the single laser which generates the light beam is not shown. The beam is illustrated entering the optical system from the left side of the figure. The beam expander consists of a first, diverging lens 1121 and a second, converging lens 1122. The expanded beam is then passed through a holographic diffuser 1113 and a field lens 1114. The image generated by holographic diffuser 1113 and field lens 1114 lies on plane 1123. Holographic diffuser 1113 is switchable by switching device 1125. in one embodiment, switching device 1125 is a device which mechanically effects the substitution of a first hologram for a second of a different prescription. This could be accomplished by any of a number of mechanical means easily designed by a person of ordinary skill in the art of mechanical design. A second field lens 1124 is therefore located at plane 1123 to correct the rays exiting the plane.

It should be noted that the switching mechanism need not be a mechanical one. Electrically switchable holographic diffractive elements are available for use in place of mechanically switchable elements. One such electrically switchable element is made by Digilens. If such an element is used, selection of alternate illumination images is a matter of applying a corresponding signal to the diffractive element.

Referring to FIGURE 51, a second illustration of the physical layout of the system is shown. In this figure, switching device 1125 is not shown. Instead, the figure depicts the movement of the diffusers. In this instance, diffuser 1113a is shown being switched out of the optical path, and diffuser 1113b is shown being inserted in its place.

Because the particular cone of light emitted from each point on a diffuser (and the resultant image) is characteristic of that particular diffuser prescription, changing the illumination image is a matter of replacing the current diffuser with a different one. As indicated in FIGURE 50, the holographic diffusers are coupled to a switching mechanism. The switching mechanism is configured to move the diffusers alternately in and out of the optical path. The switching mechanism may comprise any suitable means for moving the diffusers. In one embodiment, the diffusers may be secured in a simple frame which the user can slide back and forth to switch diffusers. This is illustrated in FIGURE 52. The diffuser mechanism is shown in a second position in which diffuser 1113b is in the optical path. If the mechanism is moved to the right into a first position, diffuser 1113a will be switched into the optical path. The diffuser mechanism can be moved manually by a user, or it may be motorized so that the movement of the mechanism can be activated by an appropriate electrical signal.

FIGURE 53 shows an alternate embodiment of a diffu^{ser} switching mechanism. In this embodiment, the different diffusers are arranged in a circular structure that can be rotated to place the desired diffuser in the optical path. A ray is shown passing through the segment of the structure comprising diffuser 1113b (this ray is depicted by a series of solid lines.) If the structure is rotated, the segments comprising diffusers 1113a, 1113b, or 1113c may be switched (manually or in an automated fashion) into the optical path. Each of these diffusers produces a different characteristic image. (A ray passing through diffuser 1113a is depicted by the dotted lines – this is shown merely to illustrate the differences between the characteristic images and is not intended to show that light passes through both diffusers at the same time.

The selectability of illumination images may make the illumination system particularly suitable for use as a component of an optical switching system. For example, an optical signal generated by the laser light source may be processed according to a first prescription if it is desired to input the signal to a first set of optical fibers, and a second prescription if it is desired to input the signal to a second set of fibers. The respective prescriptions would generate images having dots at the locations of the corresponding fiber ends. Numerous other uses are also possible.

The benefits and advantages which may be provided by the present invention have been described above with regard to specific embodiments. These benefits and advantages, and any elements or limitations that may cause them to occur or to become more pronounced are not to be construed as a critical, required, or essential features of any or all of the claims. As used herein, the terms "comprises," "comprising," or any other variations thereof, are intended to be interpreted as non-exclusively including the elements or limitations which follow those terms. Accordingly, a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to the claimed process, method, article, or apparatus.

While the present invention has been described with reference to particular embodiments, it should be understood that the embodiments are illustrative and that the scope of the invention is not limited to these embodiments. Many variations, modifications, additions and improvements to the embodiments described above are possible. It is contemplated that these variations, modifications, additions and improvements fall within the scope of the invention as detailed within the following claims.

CLAIMS

1. A system comprising:

a light source configured to emit a highly collimated light beam;

a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom; and

a field lens configured to focus the diffraction pattern into an image.

2. The system of claim 1 further comprising a field lens configured to correct the telecentricity of the image.

3. The system of claim 1 further comprising an additional light source configured to emit an additional highly collimated light beam, wherein the controlled angle diffuser is configured to receive the additional highly collimated light beam and to generate a diffraction pattern therefrom, and wherein the field lens is configured to focus the diffraction pattern of the additional highly collimated light beam into an additional image which is identical to and superimposed on the first image.

4. The system of claim 1 wherein the light source comprises one of the group consisting of: a laser; a light emitting diode; and an arc lamp.

5. The system of claim 1 further comprising a beam expander positioned between the light source and the controlled angle diffuser, wherein the beam expander is configured to expand the diameter of the light beam and to maintain the collimation of the light beam.

6. The system of claim 5 wherein the beam expander is configured to expand the light beam asymmetrically.

7. The system of claim 1 wherein the controlled angle diffuser comprises a holographic diffuser.

8. The system of claim 7 wherein the holographic diffuser has a prescription which corresponds to an illumination image which is uniformly intense.

9. The system of claim 7 wherein the holographic diffuser has a prescription which corresponds to an illumination image which is rectangular.

10. The system of claim 1 wherein the controlled angle diffuser comprises one of the group consisting of: a refractive lenslet array; a bulk scattering material; and a diffraction element.

11. The system of claim 1 wherein substantially all of the light beam emitted by the light source is focused into the image.

12. The system of claim 1 further comprising a beam expander positioned between the light source and the controlled angle diffuser and configured to expand the diameter of the light beam, wherein the numerical aperture of light at the image is controlled by the diameter of the expanded light beam.

13. The system of claim 1 wherein the controlled angle diffuser is configured to generate a diffraction pattern from the highly collimated light beam such that the diffraction pattern is focused into an image which is rectangular and uniformly intense.

14. A method comprising:

providing a highly collimated beam of light;

diffracting the beam of light using a controlled angle diffuser;

focusing the diffracted light into an illumination image; and

illuminating an imager with the illumination image.

15. The method of claim 12 wherein diffracting the beam of light using a controlled angle diffuser comprises diffracting the beam of light using a holographic diffuser.

16. The method of claim 12 wherein providing a highly collimated beam of light comprises providing a laser light beam.

17. The method of claim 12 wherein focusing the diffracted light into an illumination image and illuminating an imager with the illumination image comprises focusing the diffracted light into an illumination image which lies on an imager.

18. An illumination system for a display device comprising:

a laser light source configured to emit a highly collimated light beam;

a holographic diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom; and

a field lens configured to focus the diffraction pattern into an illumination image, wherein the illumination image has shape and intensity characteristics which match an imager of the display device.

19. The illumination system of claim 18 wherein substantially all of the light beam emitted by the laser light source is focused into the illumination image.

20. The illumination system of claim 18 wherein the illumination system is configured to generate an identical image from each portion of the light beam and to superimpose the identical images to form the illumination image.

21. A system comprising:
a plurality of light sources configured to emit highly collimated light beams;
a controlled angle diffuser configured to receive the highly collimated light beams and to generate diffraction patterns therefrom; and
a field lens configured to focus the diffraction patterns into identical, overlapping images.

22. A system comprising:
a light source configured to emit a highly collimated light beam;
a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom;
a mechanism configured to move the controlled angle diffuser laterally with respect to an optical axis; and
a field lens configured to focus the diffraction pattern into an image.

23. A system comprising:
a light source configured to emit a highly collimated light beam;
a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom; and
a field lens configured to focus the diffraction pattern into an image, wherein the image is offset from an optical axis of the light beam by an amount sufficient to displace a zero-order light leak from the image.

24. A system comprising:
a plurality of light sources configured to emit highly collimated light beams of different wavelengths;
a split controlled angle diffuser configured to receive the highly collimated light beams and to generate a diffraction pattern corresponding to each light beam; and

a field lens configured to focus the diffraction patterns into images, wherein each of the images is identical and superimposed on the other images.

25. A system comprising:
a plurality of light sources configured to emit highly collimated light beams;
a beam combiner configured to combine the highly collimated light beams;
an achromatic controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom; and
a field lens configured to focus the diffraction pattern into an image.

26. A system comprising:
a plurality of light sources configured to emit highly collimated light beams;
a controlled angle diffuser configured to receive the highly collimated light beams and to generate diffraction patterns therefrom; and
a field lens configured to focus the diffraction pattern into an image, wherein the image is offset from an optical axis of the light beam by an amount sufficient to displace a zero-order light leak from the image.

27. A system comprising:
a plurality of optical processors, each having a monochromatic light source configured to emit a highly collimated light beam, a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom, and a field lens configured to focus the diffraction pattern into an image; and
an image combiner positioned following the images and configured to combine the monochromatic images into a single polychromatic image, and to relay the polychromatic image to relay optics.

28. A system comprising:
a plurality of optical processors, each having a monochromatic light source configured to emit a highly collimated light beam, a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom, and a field lens configured to focus the diffraction pattern into an image; and
an image combiner positioned following the field lens of each optical processor and configured to combine the monochromatic images into a single polychromatic image.

29. A system comprising:

a light source configured to emit a highly collimated light beam;

a controlled angle diffuser configured to receive the highly collimated light beam and to generate a diffraction pattern therefrom;

a field lens configured to focus the diffraction pattern into an illumination image;

an imager, wherein the imager is positioned to be illuminated by the illumination image and to generate an information image; and

display optics configured to project the information image onto a viewable screen.

30. The system of claim 29 further comprising

one or more additional light sources configured to emit highly collimated light beams, one or more controlled angle diffusers configured to receive the highly collimated light beams and to generate diffraction patterns therefrom, and one or more field lenses configured to focus the diffraction patterns into images; and

an image combiner positioned following each field lens and configured to combine the images into a single image.

31. The system of claim 30 further comprising

a beam splitter positioned between each field lens and an imager, wherein the beam splitter is configured to allow the images to illuminate the imager and to redirect light from the imager into display optics.

32. A system comprising:

a light source configured to emit a highly collimated light beam;

a diffuser mechanism which is configured to alternately position a plurality of controlled angle diffusers having different prescriptions to receive the highly collimated light beam and to generate a diffraction pattern therefrom; and

a field lens configured to focus the diffraction pattern into an image.

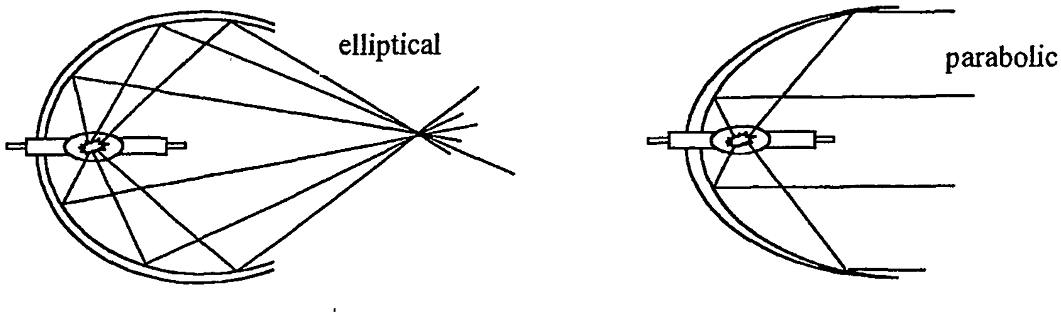

Figure 1

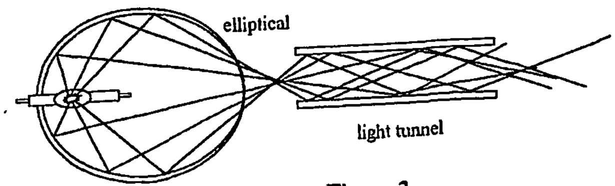

Figure 2

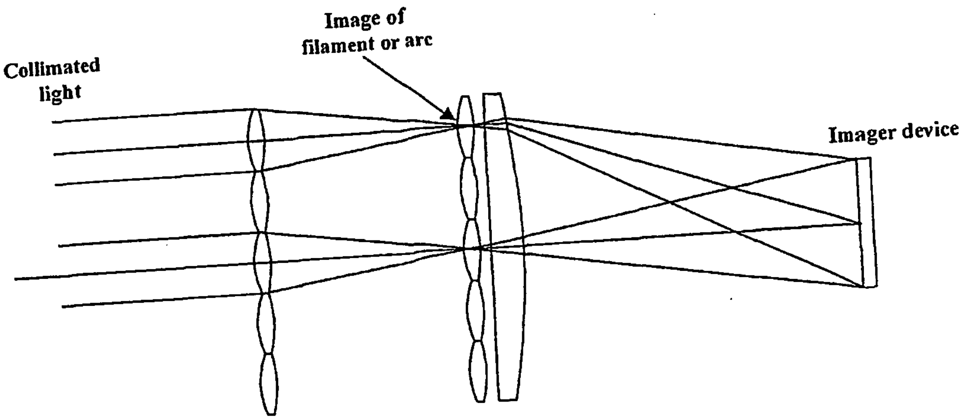

Figure 3 Lenslet array Prior Art with limited ray trace

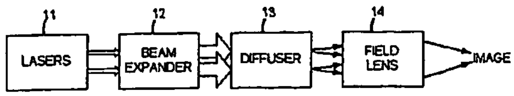

Figure 4

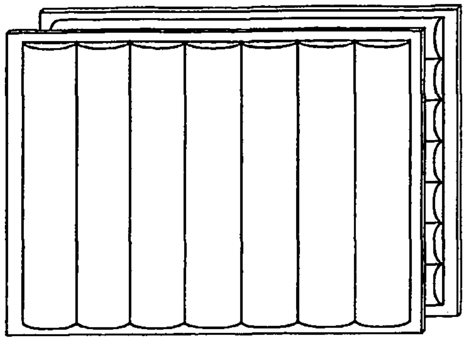

Figure 5A

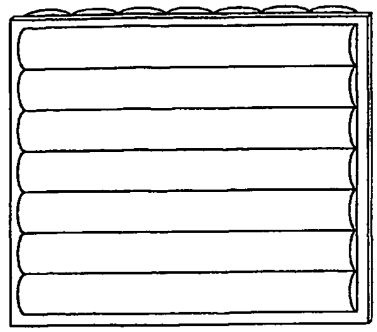

Figure 5B

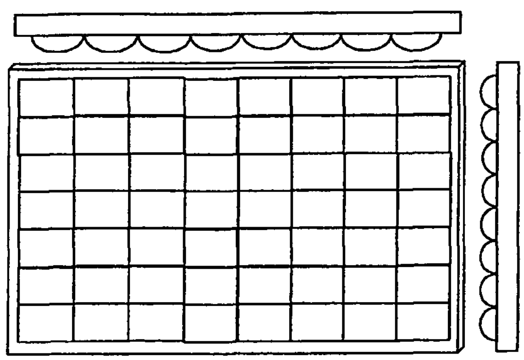

Figure 5C

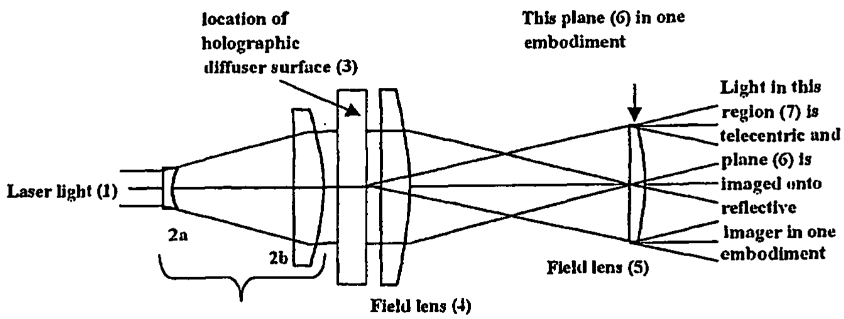
location of
holographic
diffuser surface (3)
This plane (6) in one
embodiment
Light in this
region (7) is
telecentric and
plane (6) is
imaged onto
reflective
imager in one
embodiment
Laser light (1)
2a
2b
Field lens (5)
Field lens (4)

Figure 6

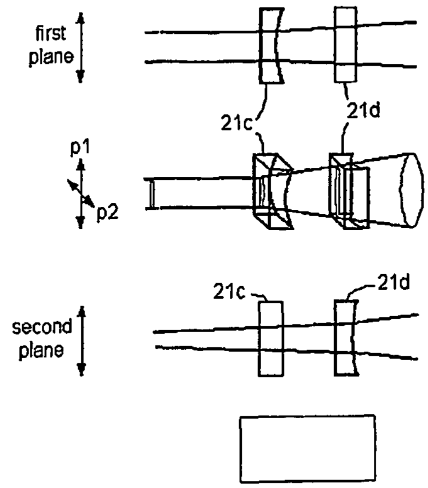

Figure 7

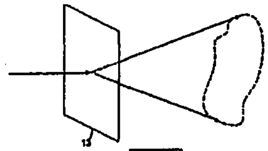

Figure 8B

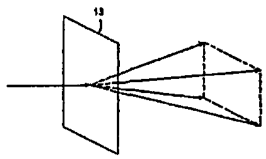

Figure 8A

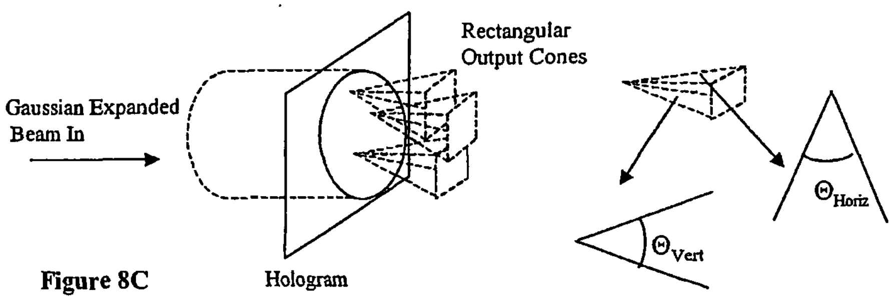

Figure 8C

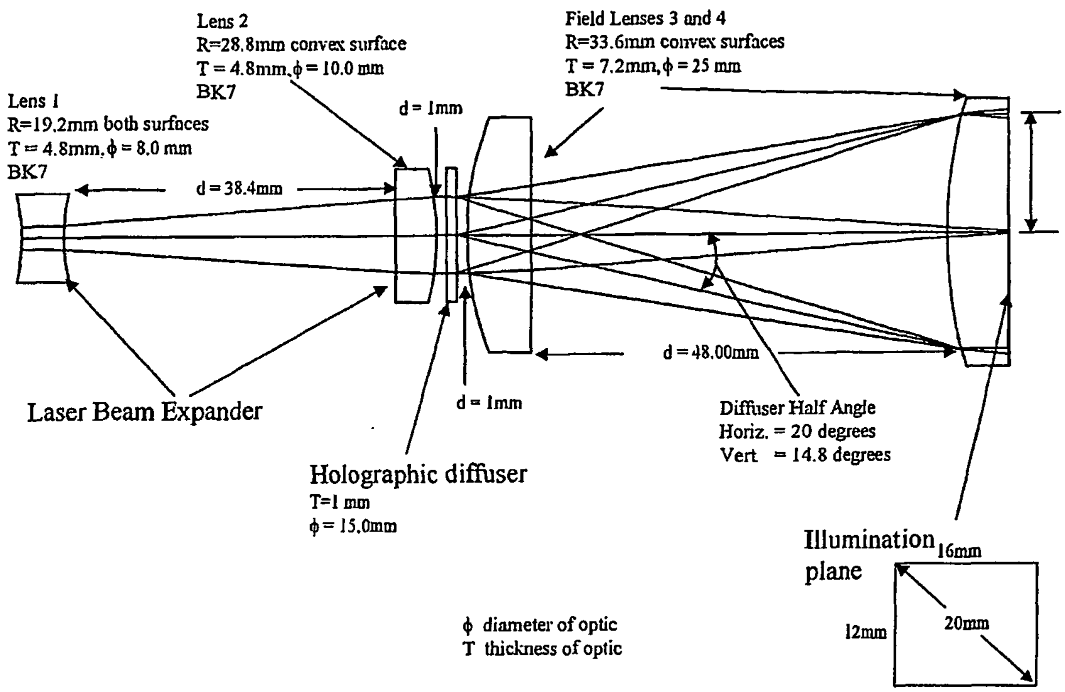
Lens 2
R=28.8mm convex surface
T = 4.8mm, ϕ = 10.0 mm
BK7
Field Lenses 3 and 4
R=33.6mm convex surfaces
T = 7.2mm, ϕ = 25 mm
BK7
Lens 1
R=19.2mm both surfaces
T = 4.8mm, ϕ = 8.0 mm
BK7
d = 1mm
d = 38.4mm
d = 48.00mm
Laser Beam Expander
d = 1mm
Diffuser Half Angle
Horiz. = 20 degrees
Vert = 14.8 degrees
Holographic diffuser
T=1 mm
ϕ = 15.0mm
Illumination plane
16mm
12mm
20mm
ϕ diameter of optic
T thickness of optic

Figure 9

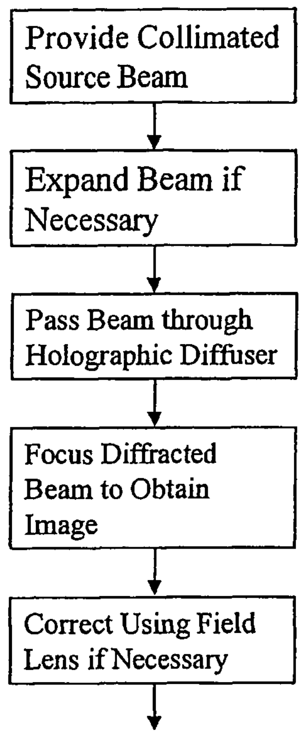
Provide Collimated Source Beam
Expand Beam if Necessary
Pass Beam through Holographic Diffuser
Focus Diffracted Beam to Obtain Image
Correct Using Field Lens if Necessary

Figure 10

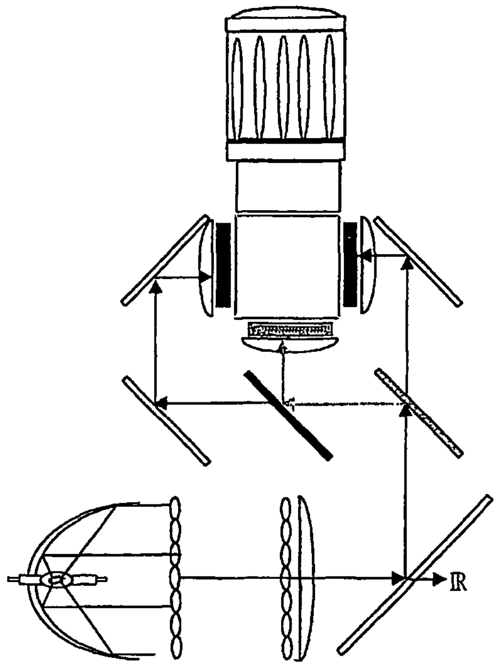

Figure 11A

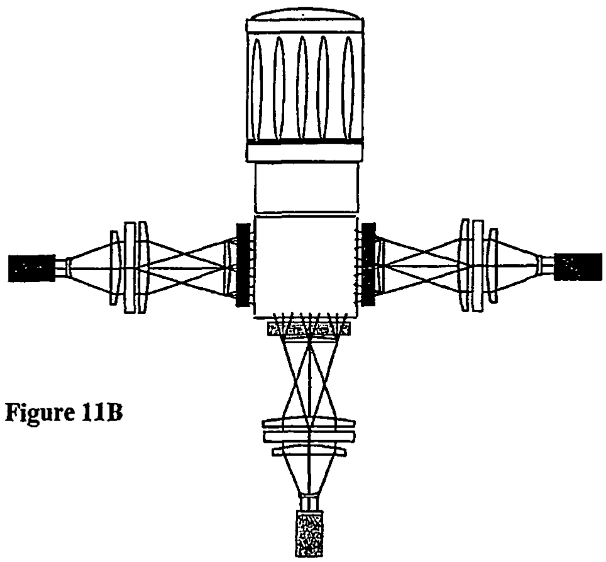

Figure 11B

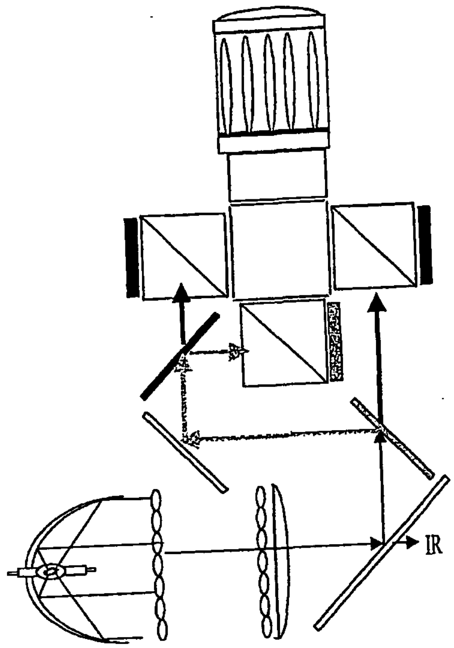

Figure 12A

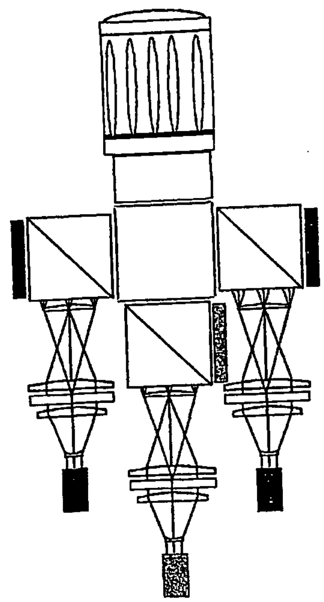

Figure 12B

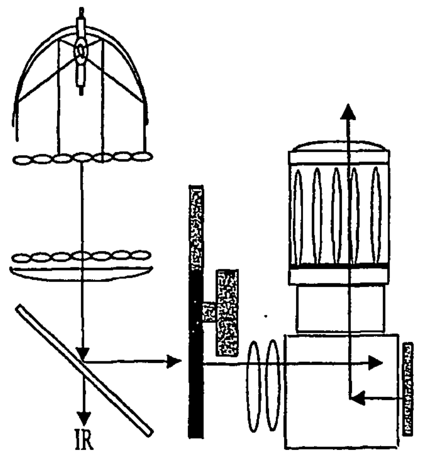

Figure 13A

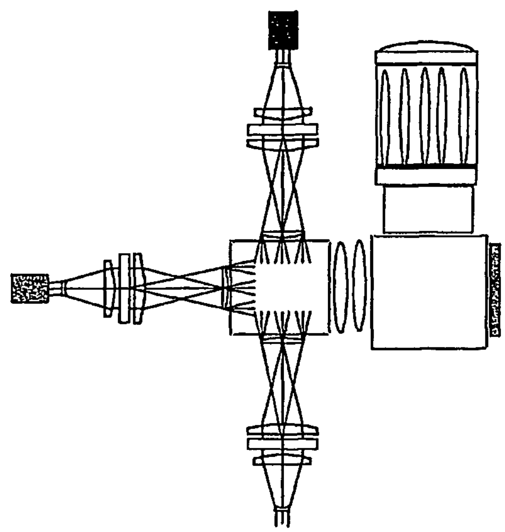

Figure 13B

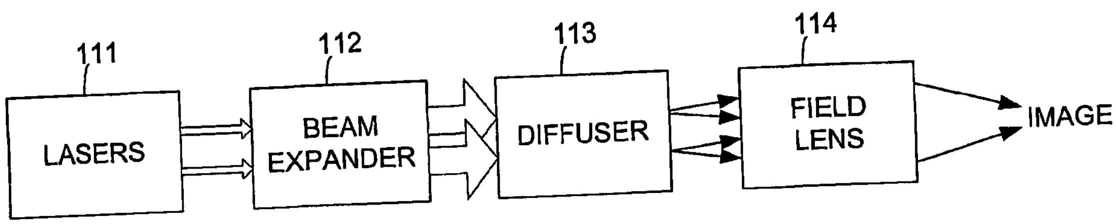
111
LASERS
112
BEAM EXPANDER
113
DIFFUSER
114
FIELD LENS
IMAGE

Fig. 14

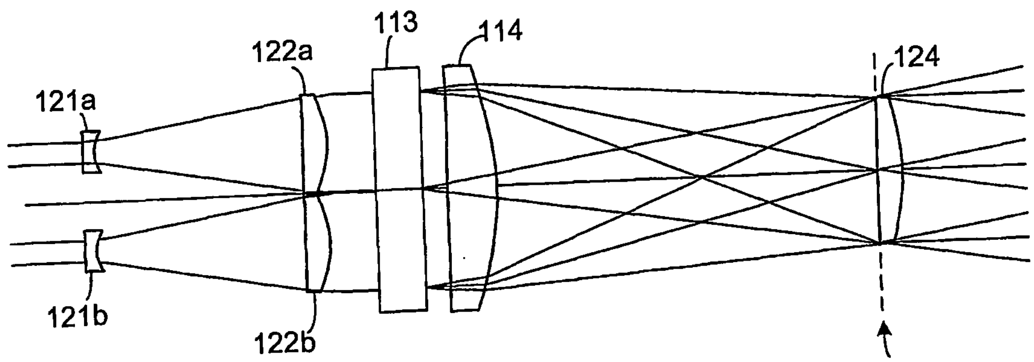

Fig. 15

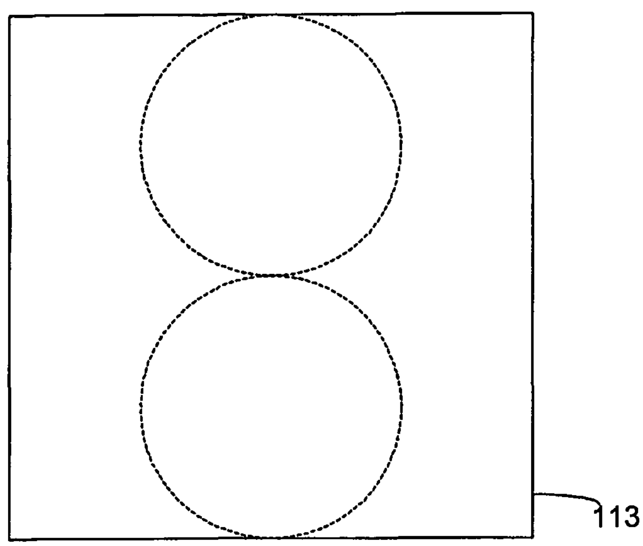

Fig. 16

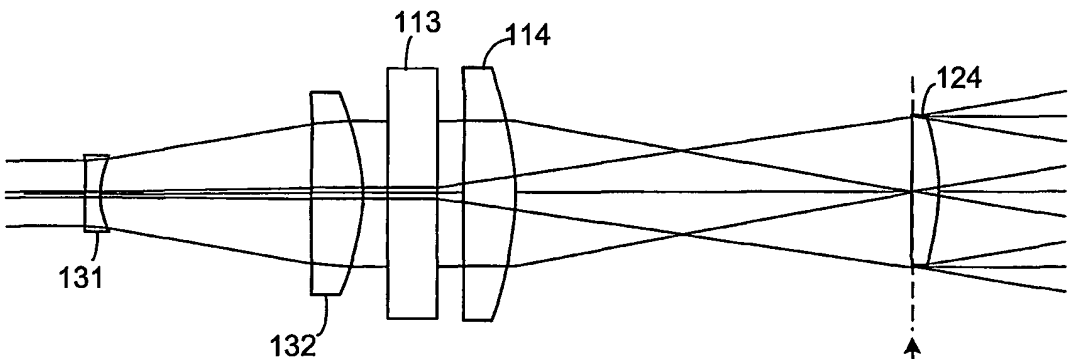

Fig. 17

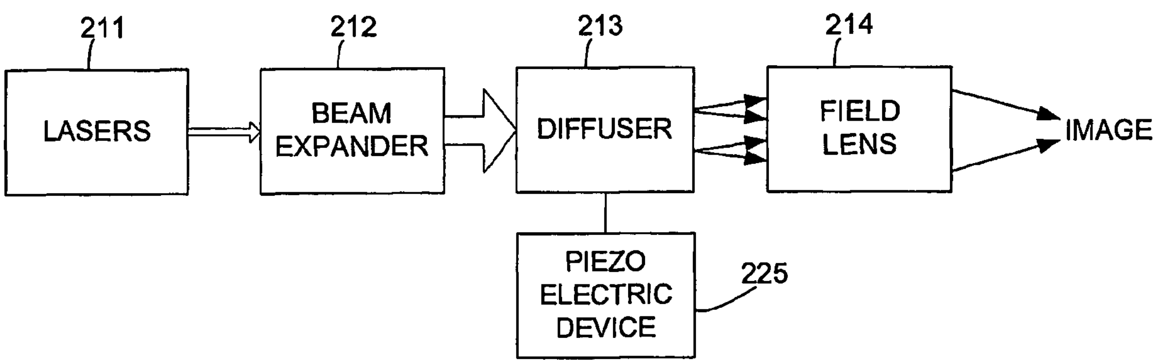
211
212
213
214
LASERS
BEAM EXPANDER
DIFFUSER
FIELD LENS
IMAGE
PIEZO ELECTRIC DEVICE
225

Fig. 18

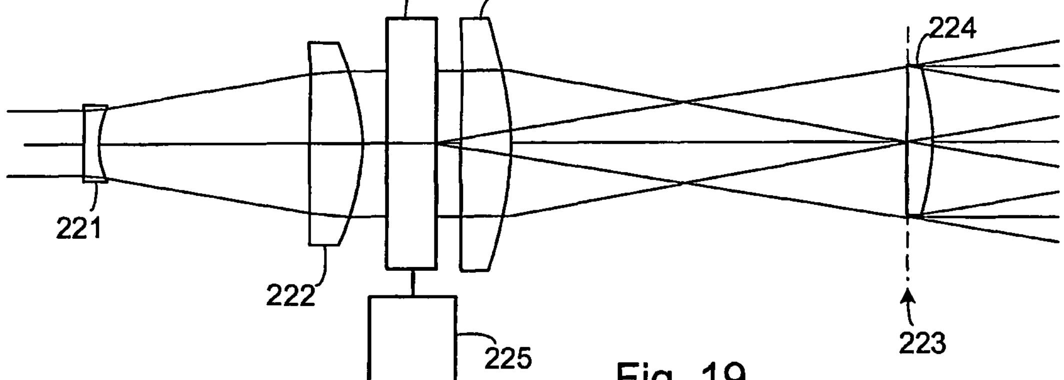

Fig. 19

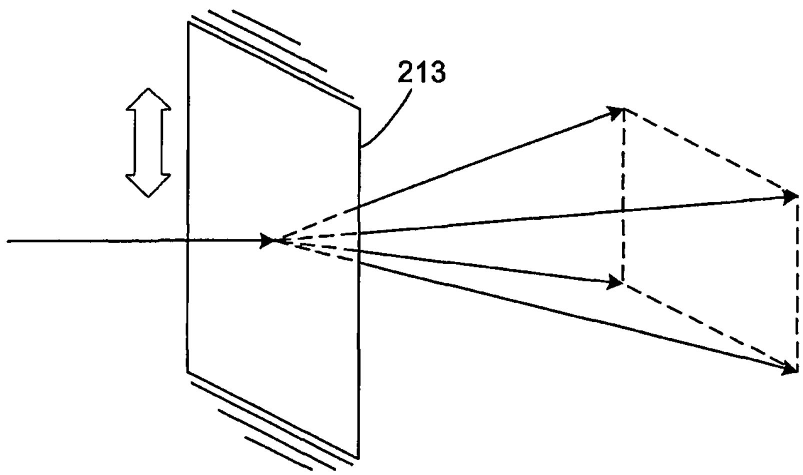

Fig. 20

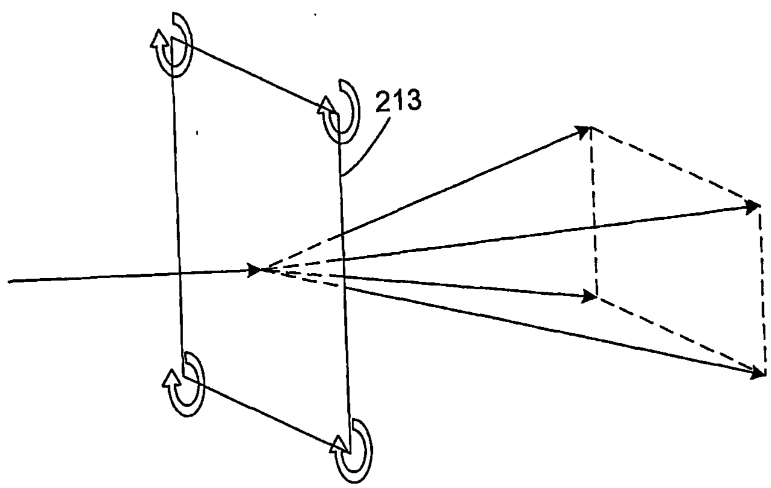

Fig.21

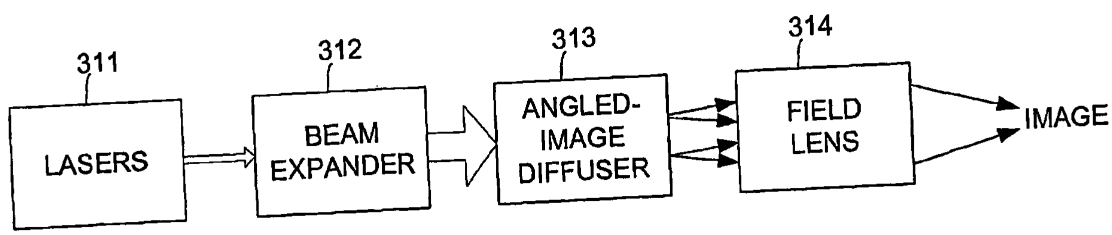
311
312
313
314
LASERS
BEAM EXPANDER
ANGLED-IMAGE DIFFUSER
FIELD LENS
IMAGE

Fig. 22

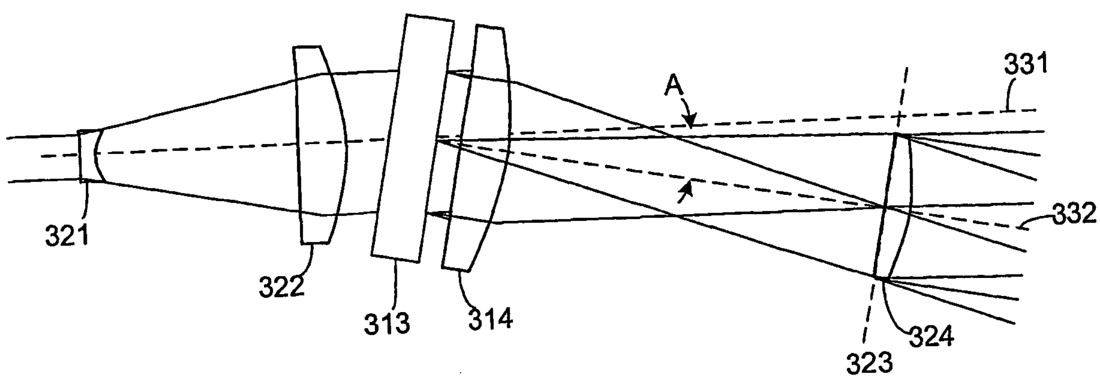

Fig. 23

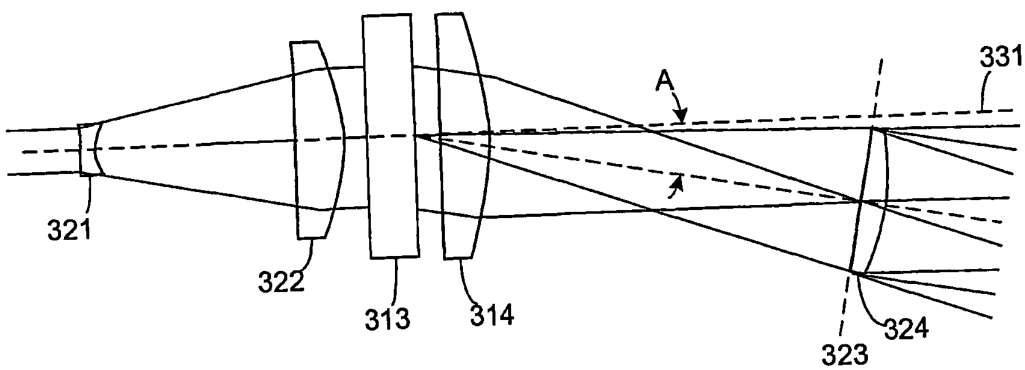

Fig. 24

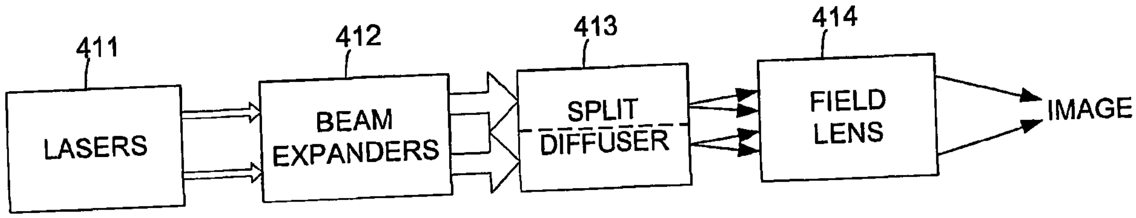
411
LASERS
412
BEAM EXPANDERS
413
SPLIT
DIFFUSER
414
FIELD LENS
IMAGE

Fig. 25

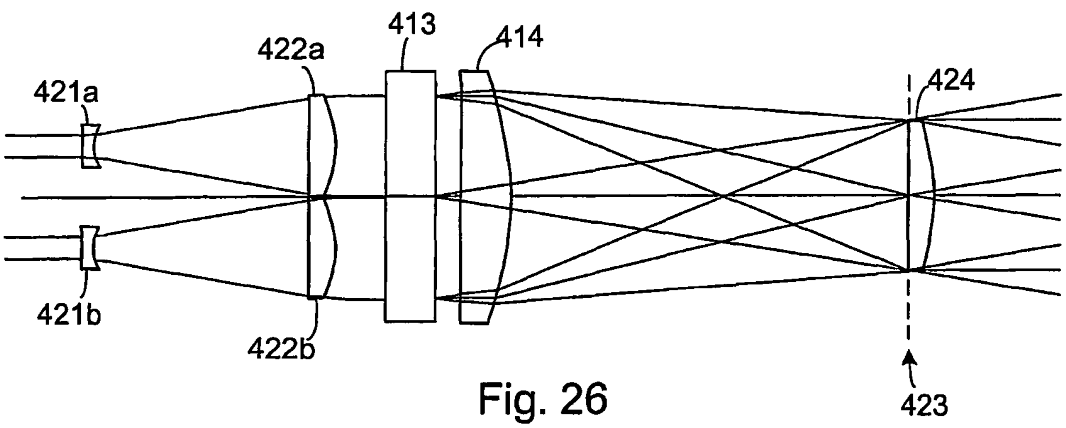

Fig. 26

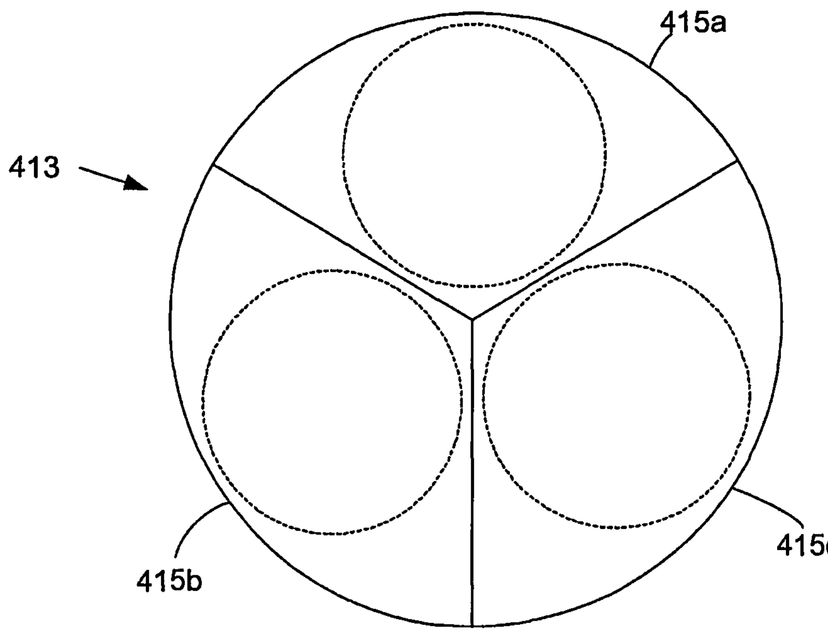

Fig. 27A

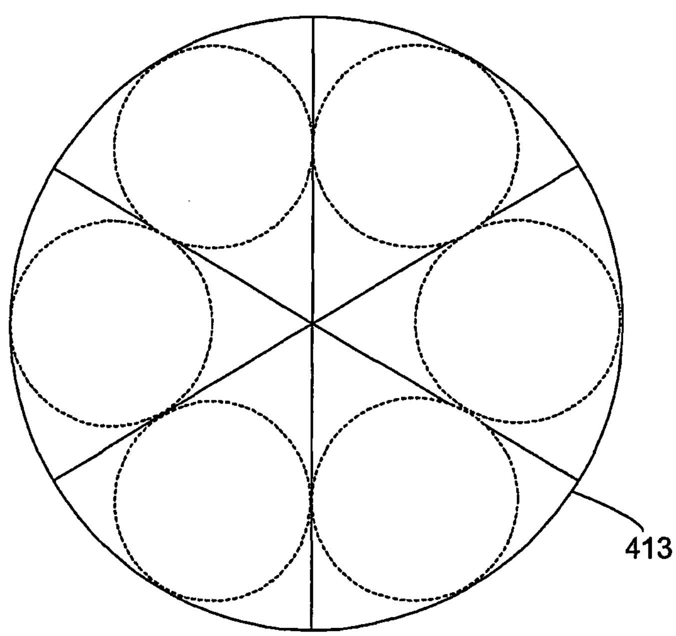

Fig. 27B

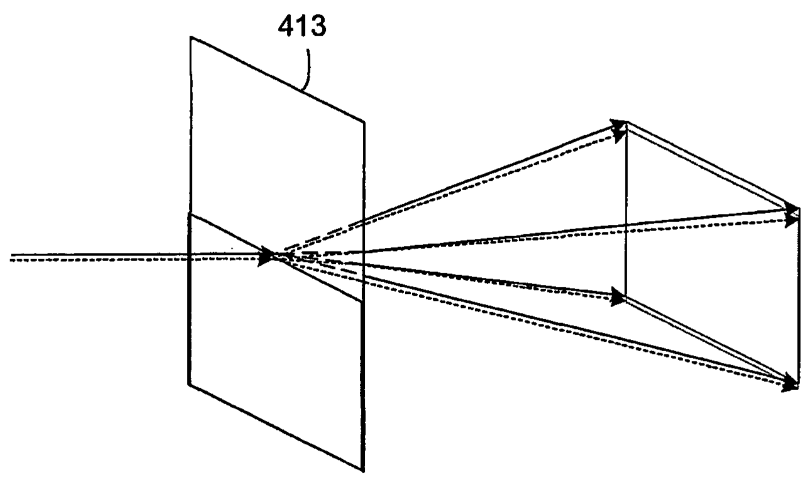

Fig. 28

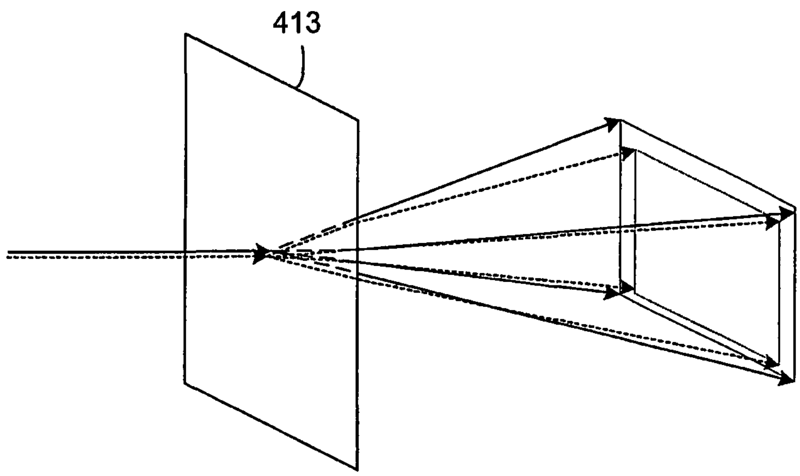

Fig. 29

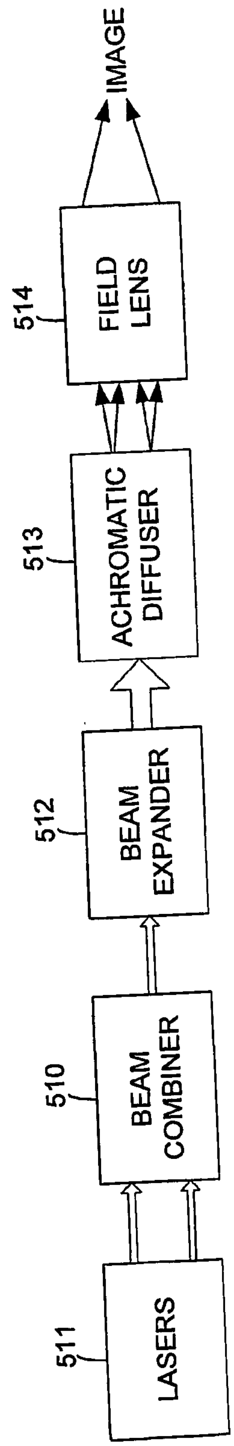
IMAGE
514
FIELD LENS
513
ACHROMATIC DIFFUSER
512
BEAM EXPANDER
510
BEAM COMBINER
511
LASERS

Fig. 30

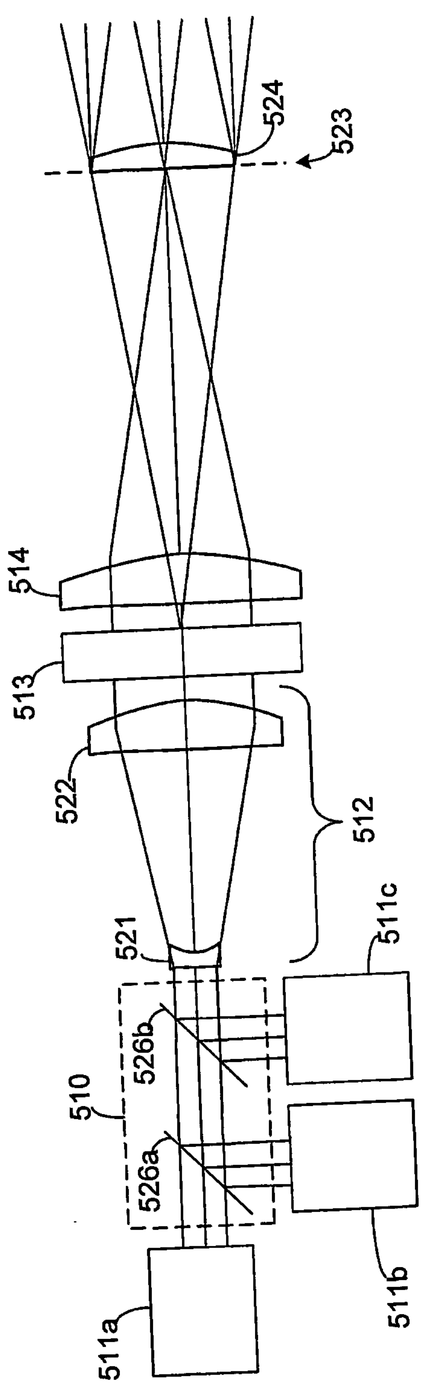

Fig. 31

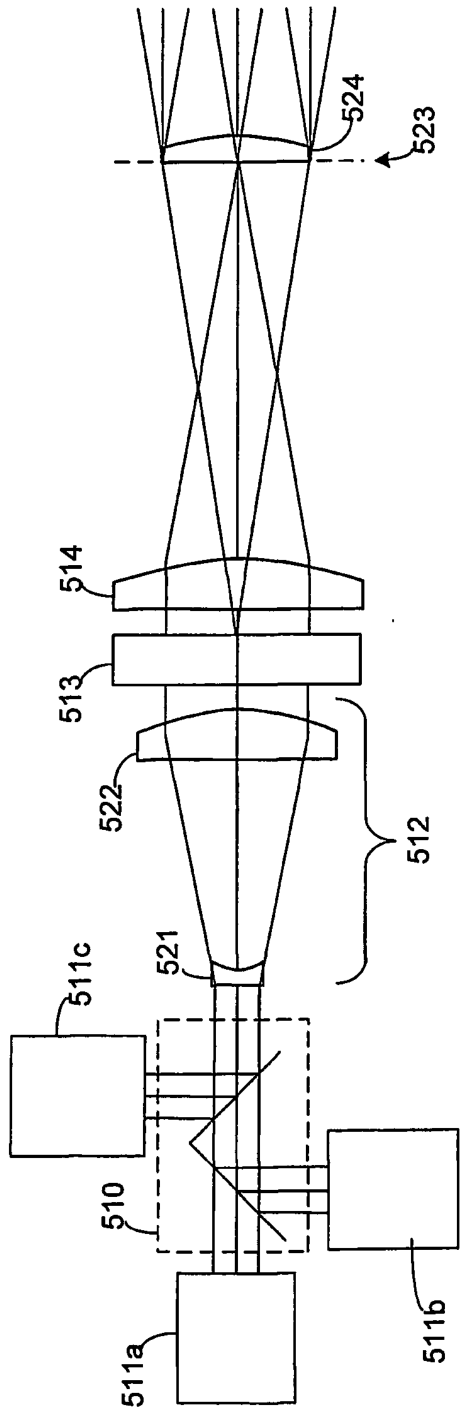

Fig. 32

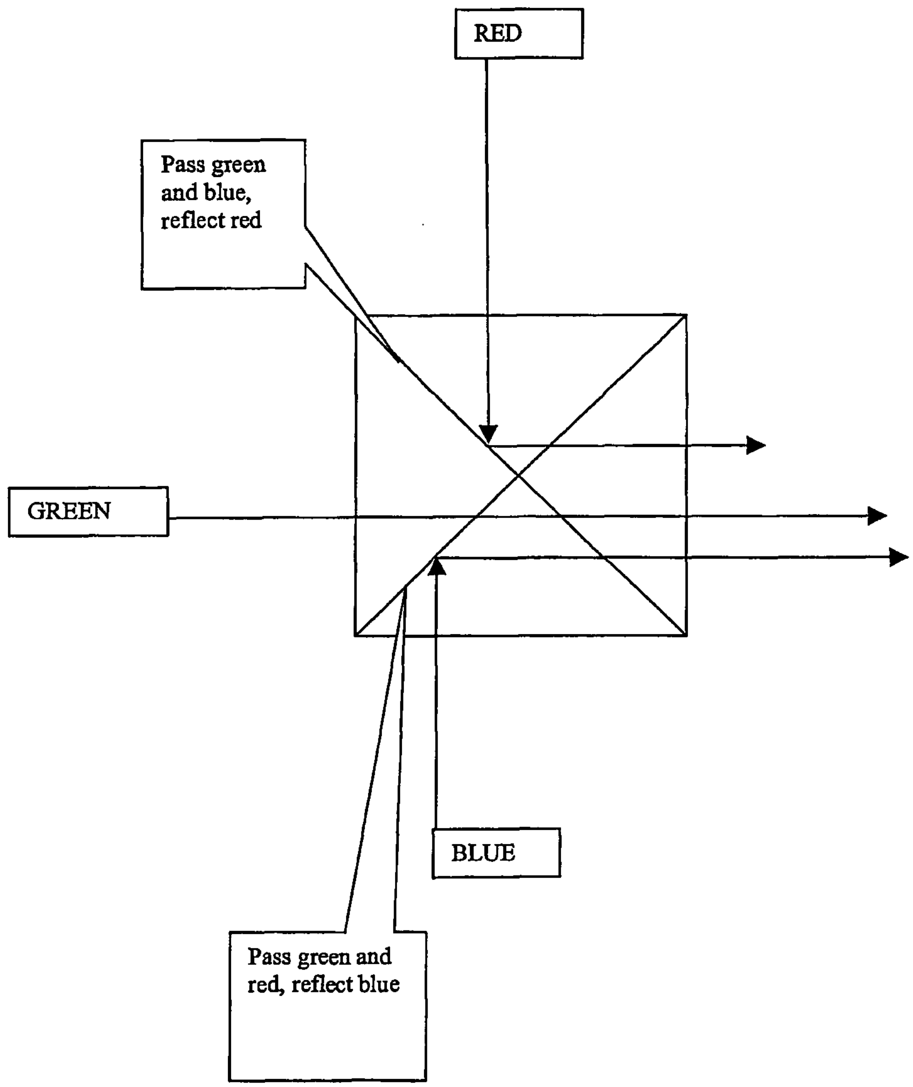
RED
Pass green and blue, reflect red
GREEN
BLUE
Pass green and red, reflect blue

Fig. 33

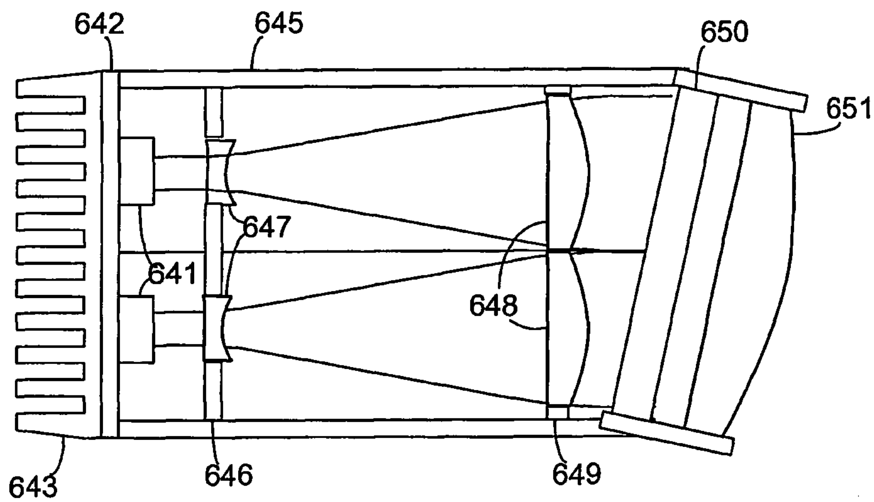

Fig. 34

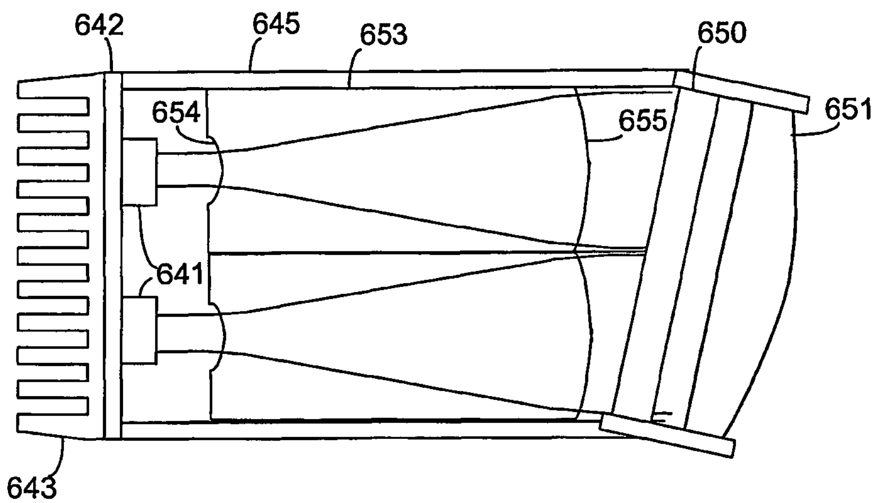

Fig. 35

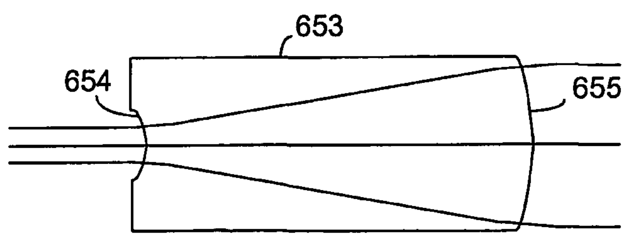

Fig. 36

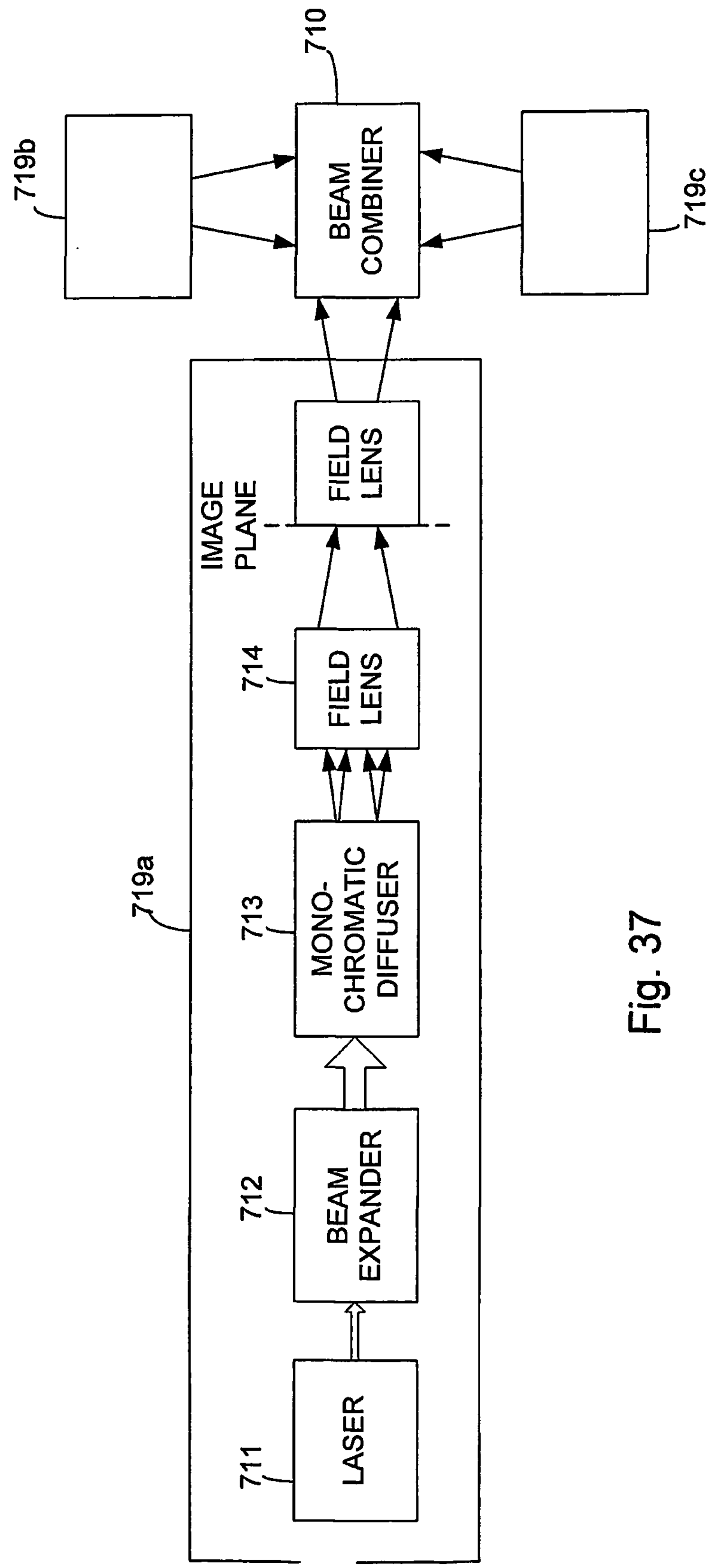
710
BEAM COMBINER
719b
719c
IMAGE PLANE
FIELD LENS
714
FIELD LENS
719a
713
MONO-CHROMATIC DIFFUSER
712
BEAM EXPANDER
711
LASER

Fig. 37

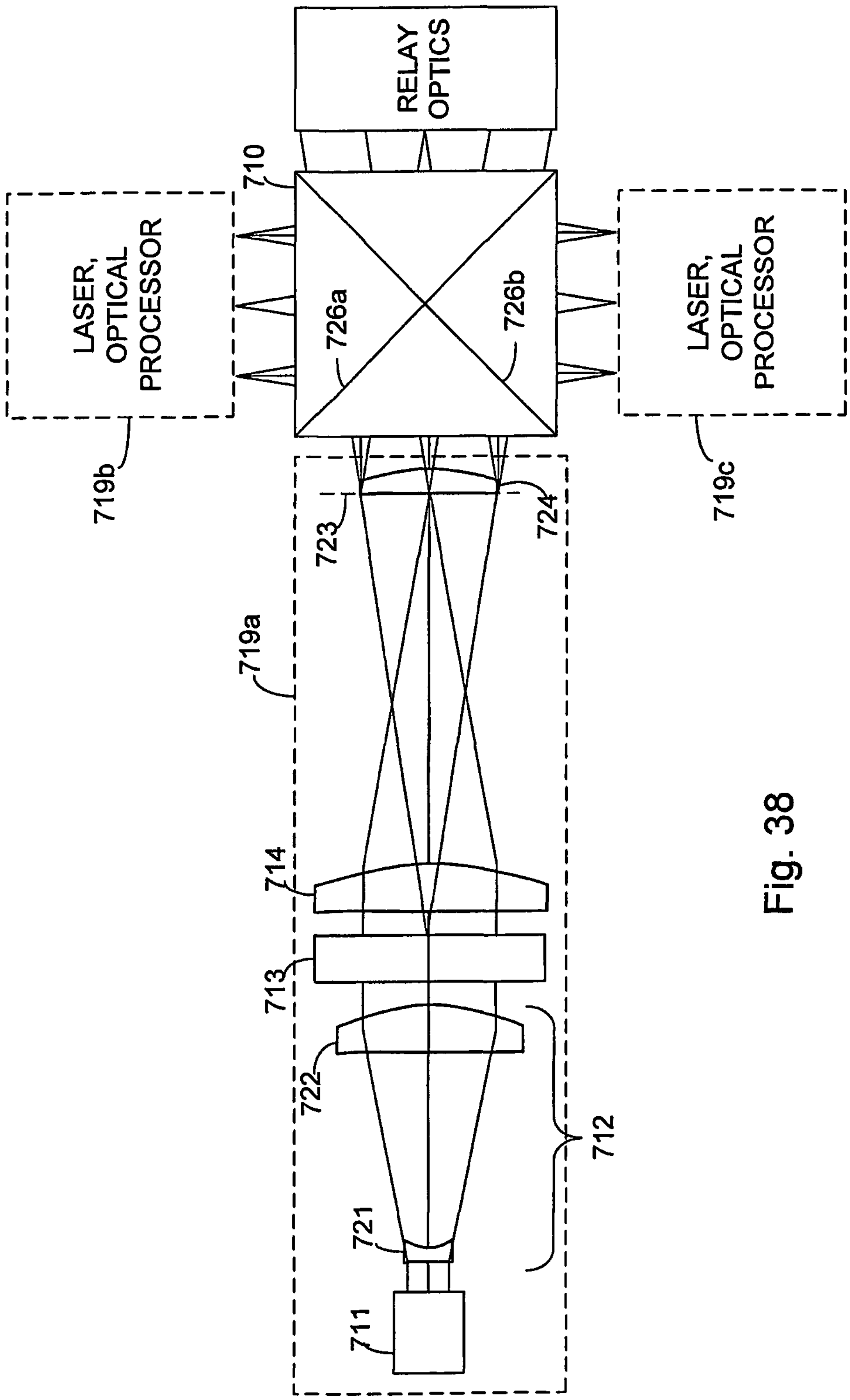
RELAY OPTICS
LASER, OPTICAL PROCESSOR
LASER, OPTICAL PROCESSOR
710
726a
726b
719b
719c
719a
723
724
714
713
722
712
721
711

Fig. 38

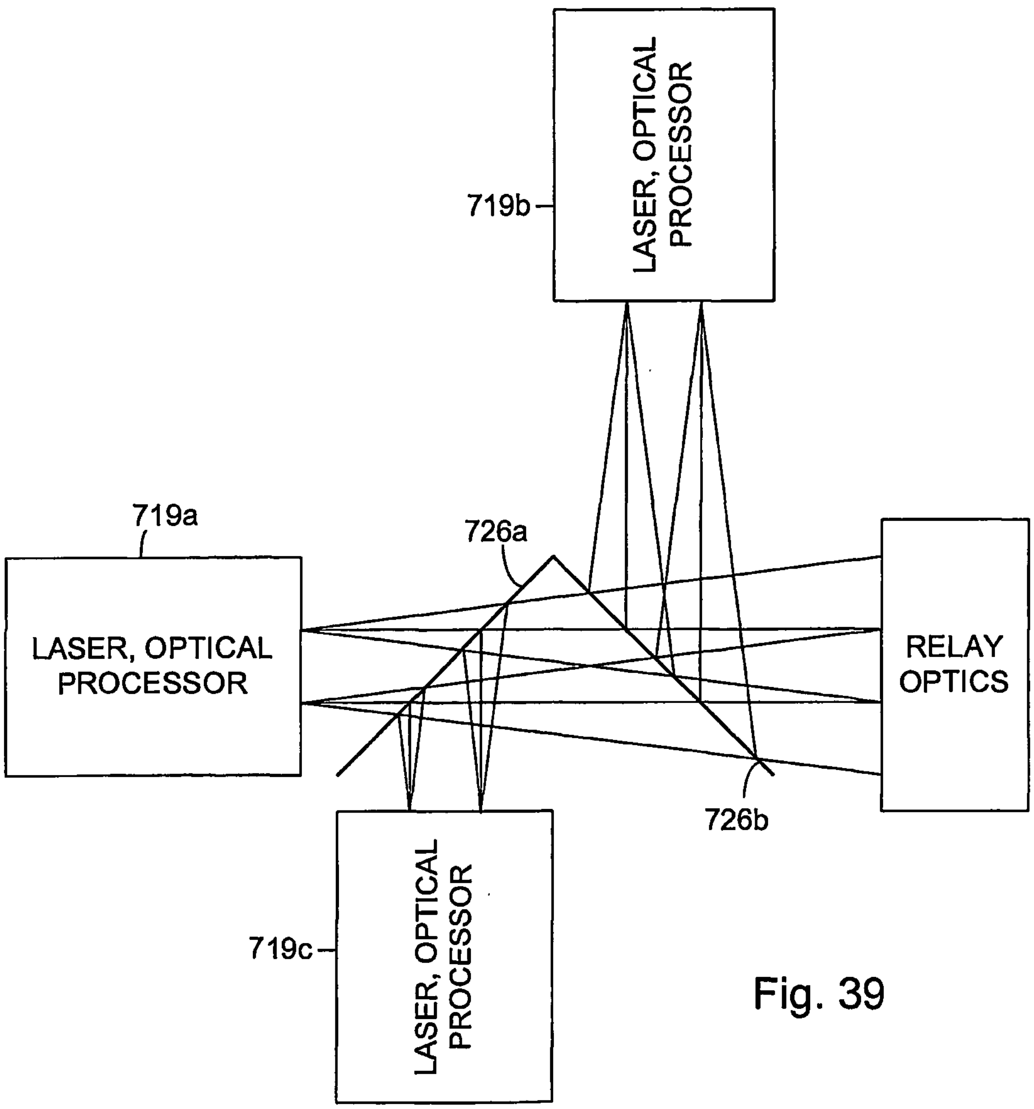
LASER, OPTICAL PROCESSOR
719b
719a
726a
LASER, OPTICAL PROCESSOR
RELAY OPTICS
726b
719c
LASER, OPTICAL PROCESSOR

Fig. 39

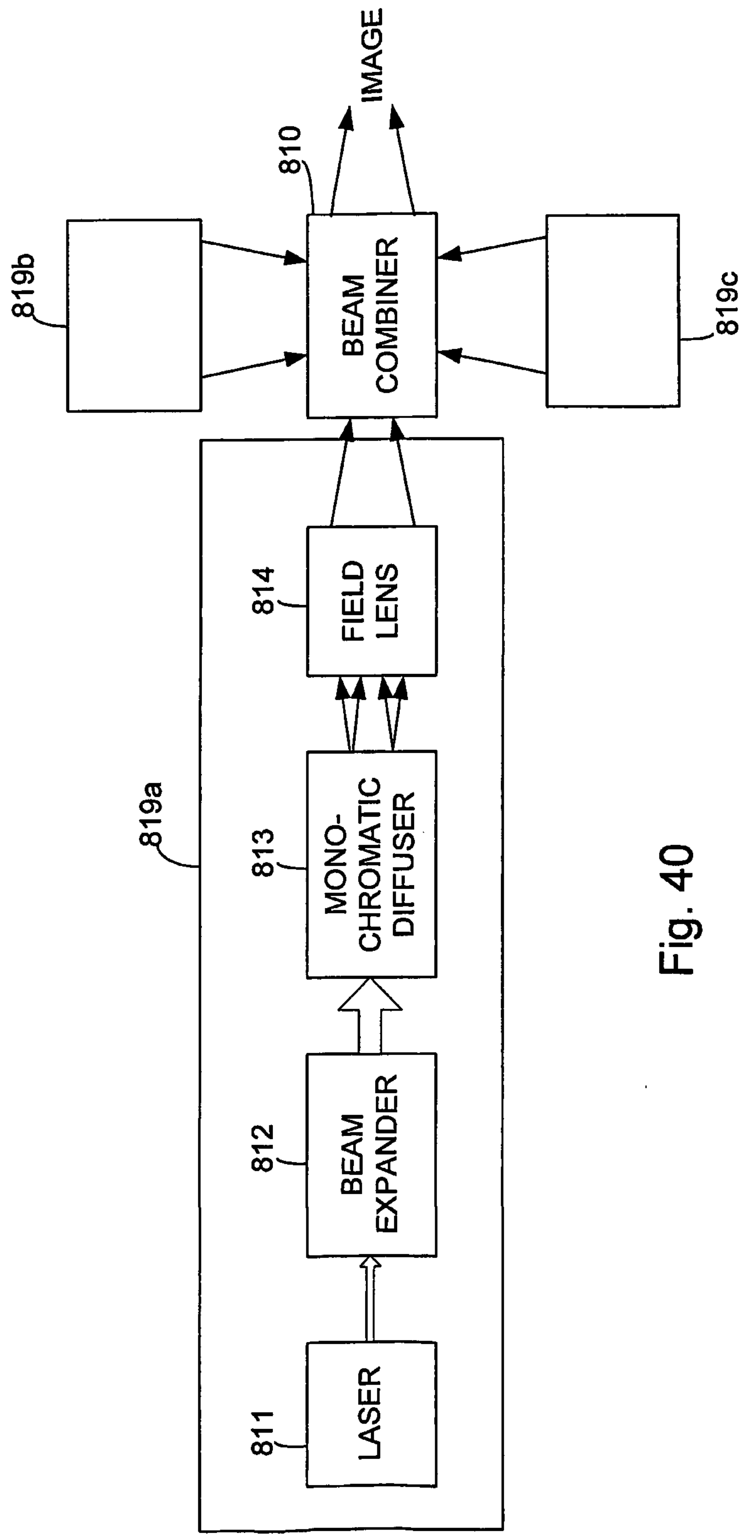
IMAGE
810
BEAM
COMBINER
819b
819c
814
FIELD
LENS
819a
813
MONO-
CHROMATIC
DIFFUSER
812
BEAM
EXPANDER
811
LASER

Fig. 40

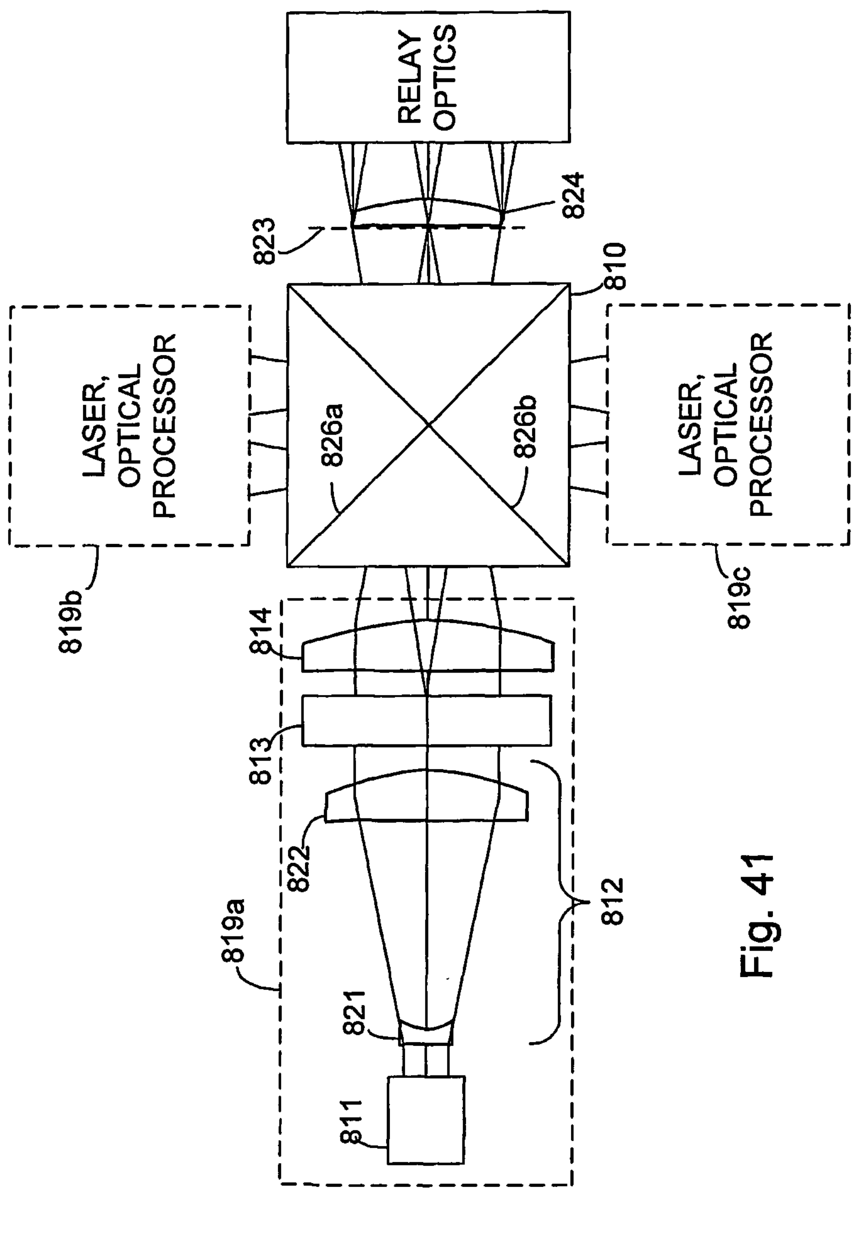
RELAY OPTICS
824
823
810
LASER, OPTICAL PROCESSOR
826a
826b
LASER, OPTICAL PROCESSOR
819b
819c
814
813
822
812
819a
821
811

Fig. 41

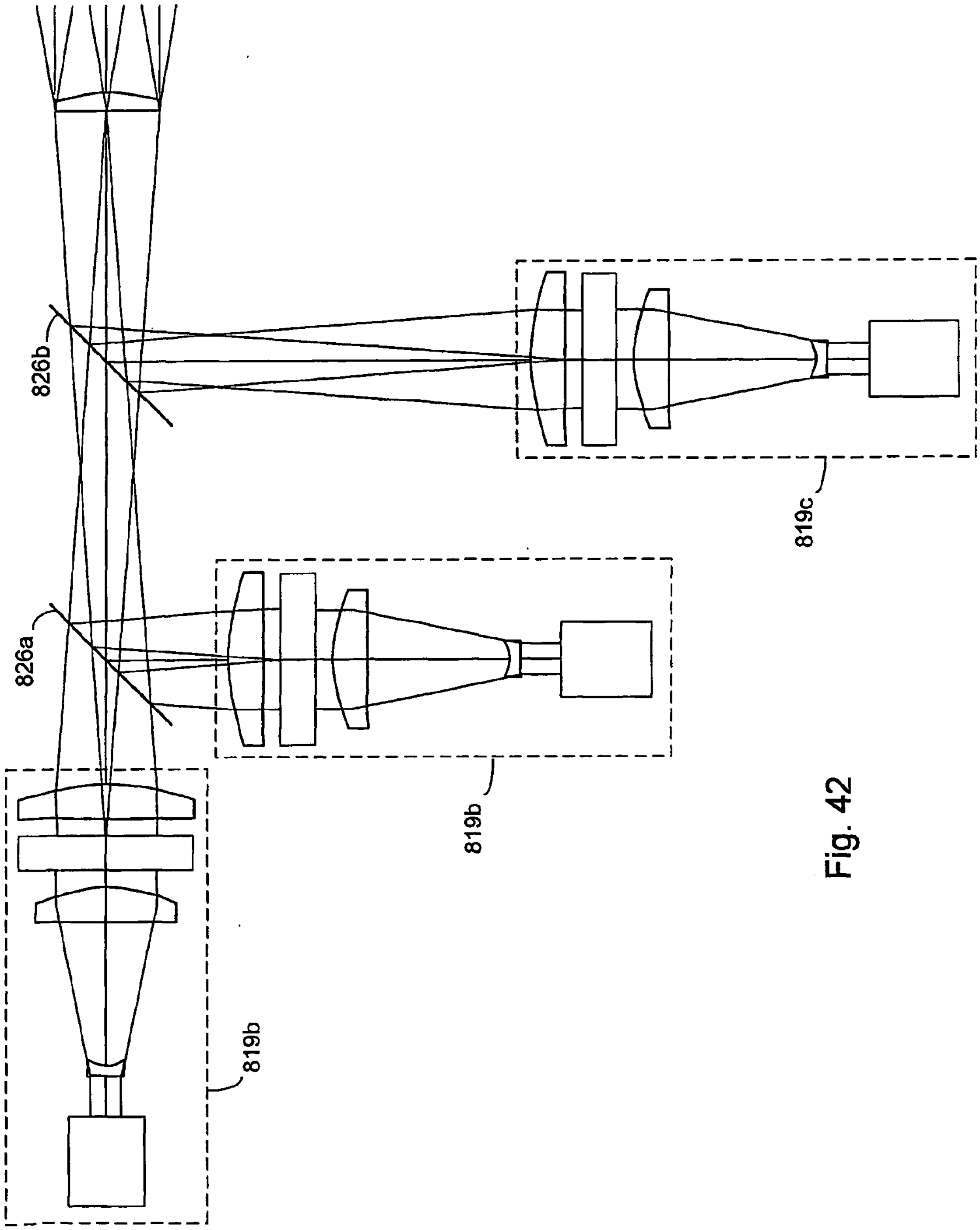

Fig. 42

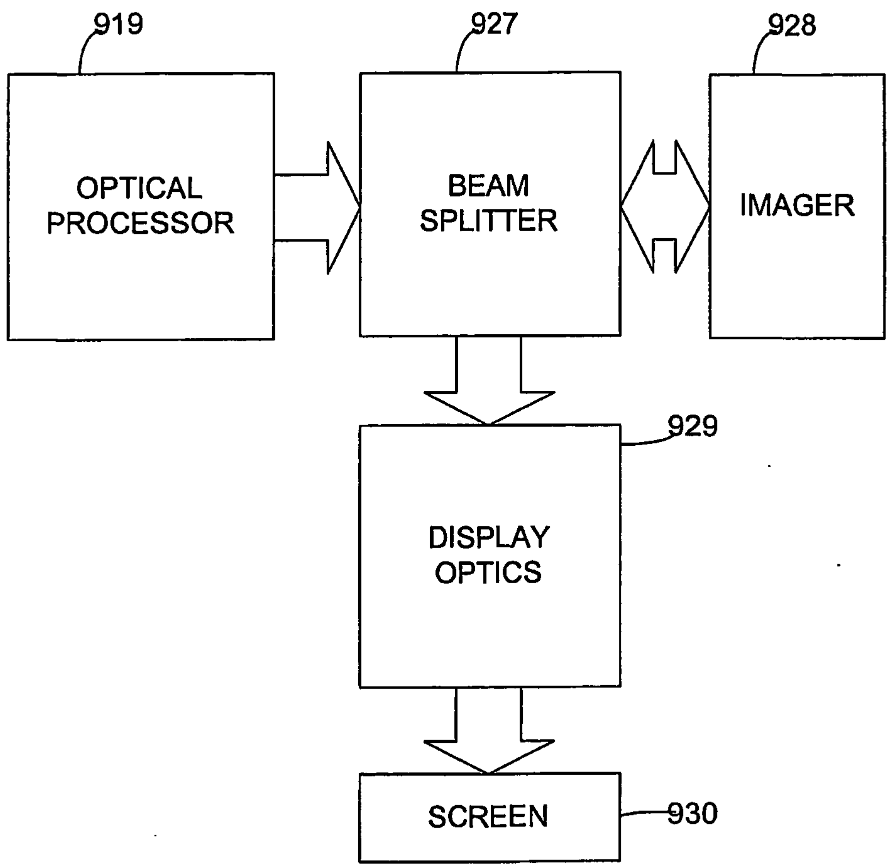
919
927
928
OPTICAL PROCESSOR
BEAM SPLITTER
IMAGER
929
DISPLAY OPTICS
SCREEN
930

Fig. 43

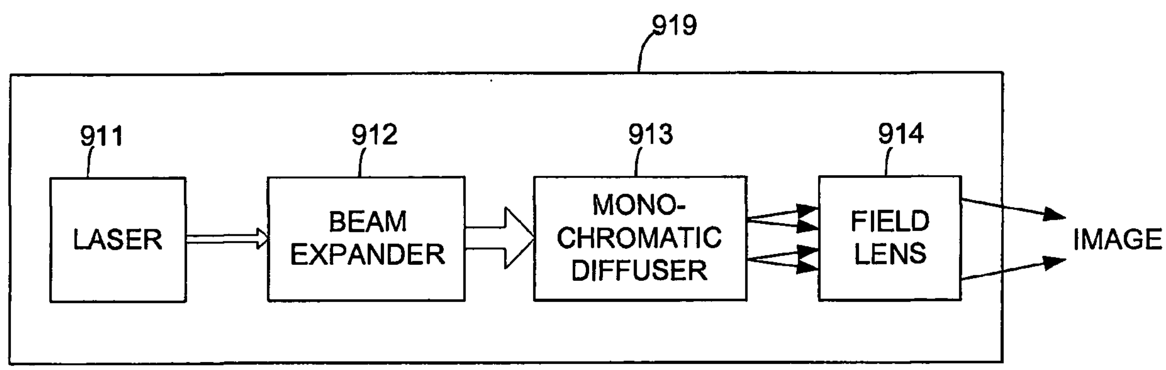
919
911
LASER
912
BEAM
EXPANDER
913
MONO-
CHROMATIC
DIFFUSER
914
FIELD
LENS
IMAGE

Fig. 44

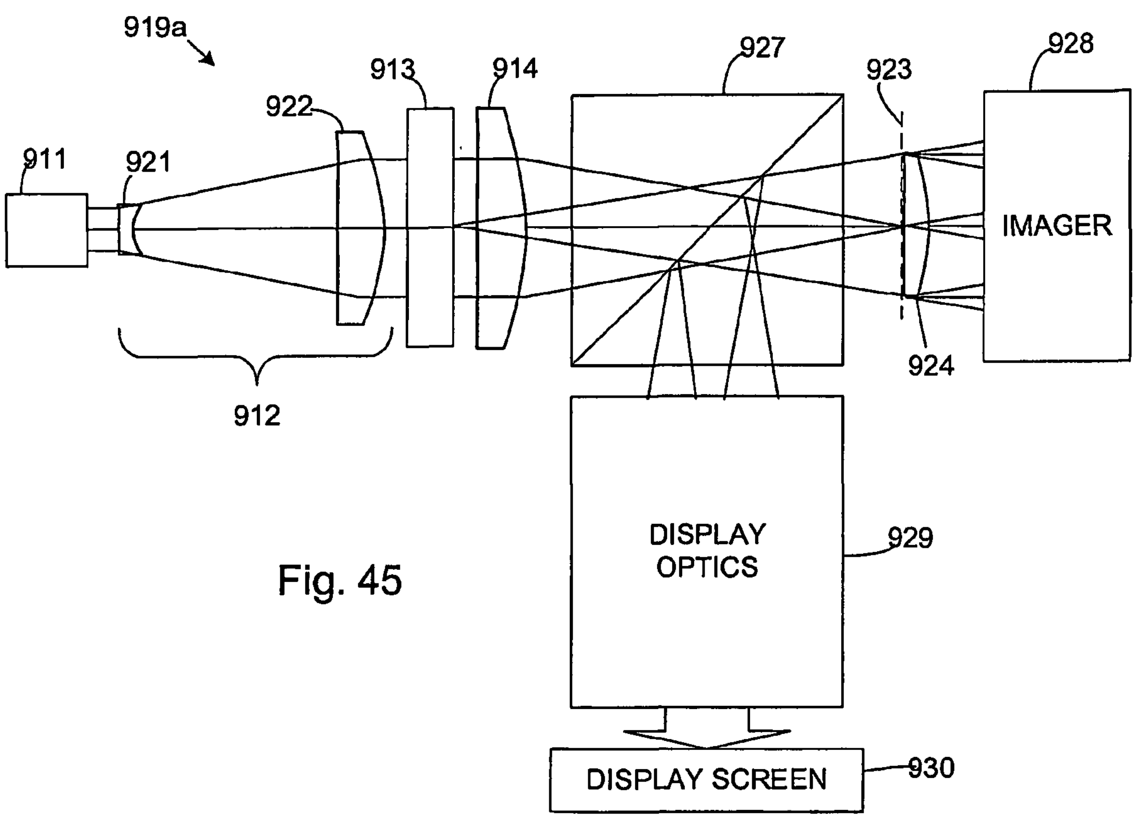
919a
913
914
927
923
928
922
911
921
IMAGER
924
912
DISPLAY OPTICS
929
DISPLAY SCREEN
930

Fig. 45

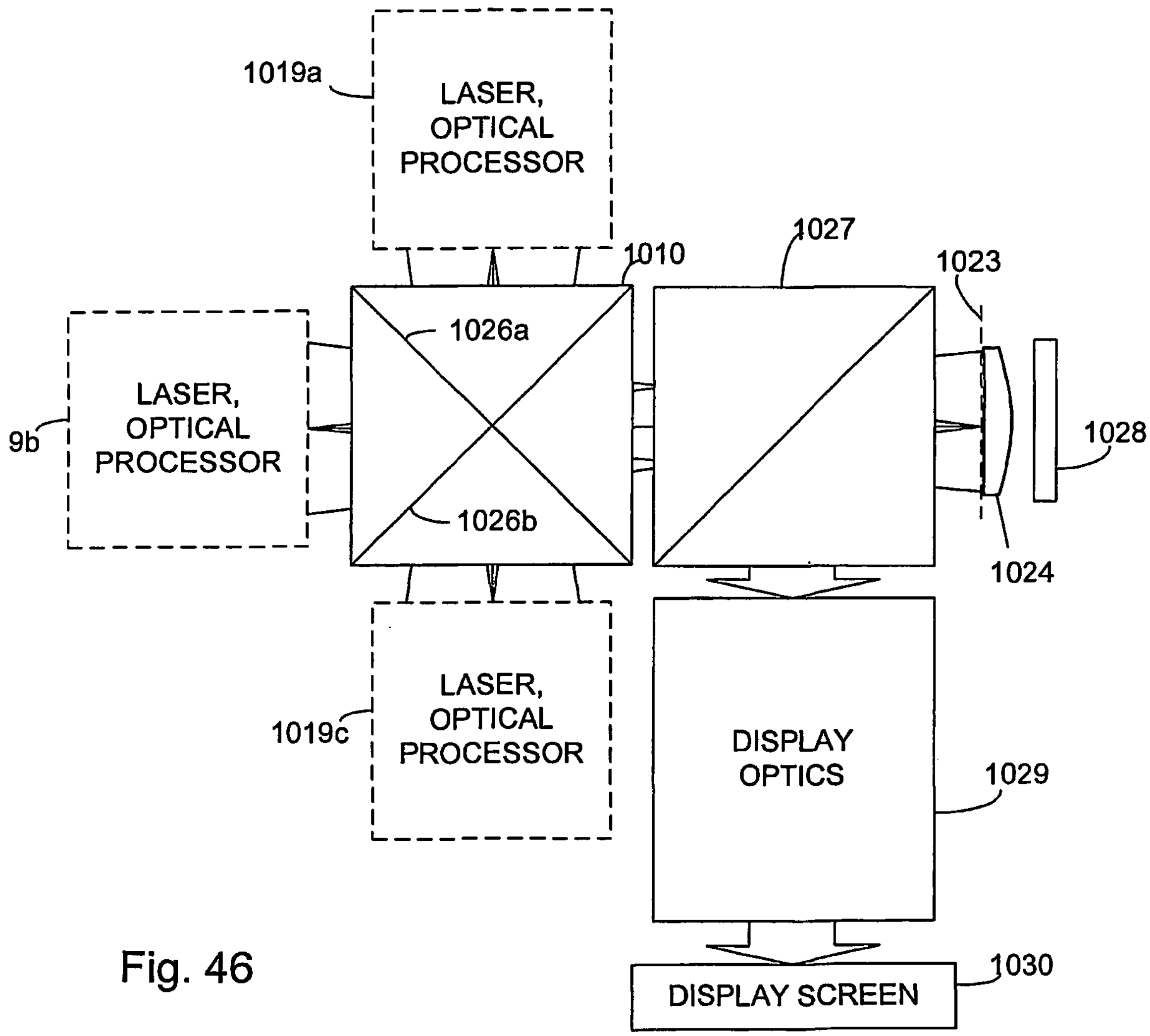
1019a
LASER, OPTICAL PROCESSOR
1010
1027
1023
1026a
9b
LASER, OPTICAL PROCESSOR
1028
1026b
1024
LASER, OPTICAL PROCESSOR
1019c
DISPLAY OPTICS
1029
1030
DISPLAY SCREEN

Fig. 46

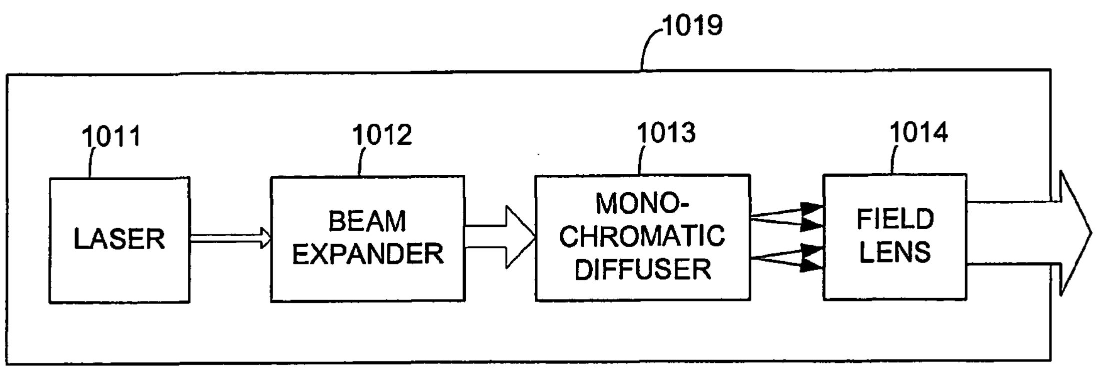
1019
1011
1012
1013
1014
LASER
BEAM
EXPANDER
MONO-
CHROMATIC
DIFFUSER
FIELD
LENS

Fig. 47

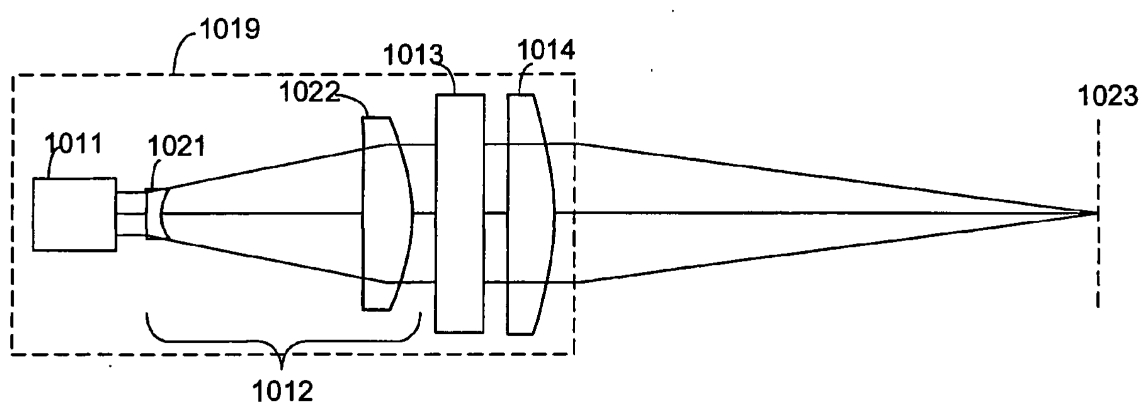

Fig. 48

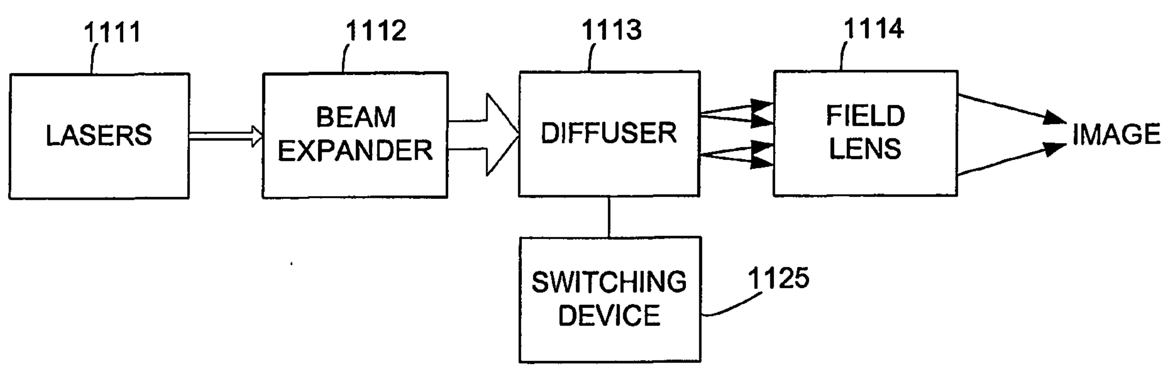
1111
LASERS
1112
BEAM EXPANDER
1113
DIFFUSER
1114
FIELD LENS
IMAGE
SWITCHING DEVICE
1125

Fig. 49

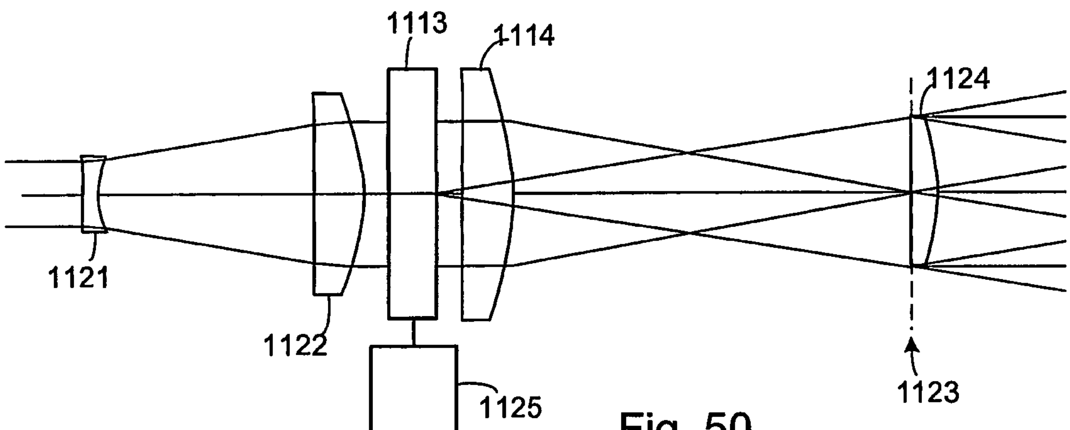

Fig. 50

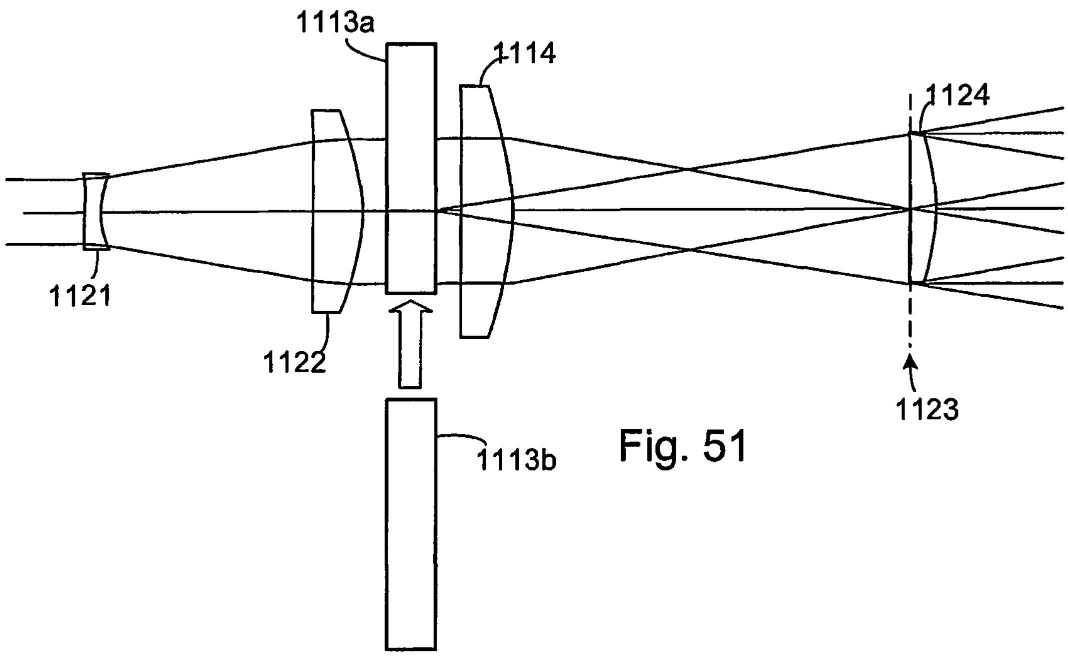

Fig. 51

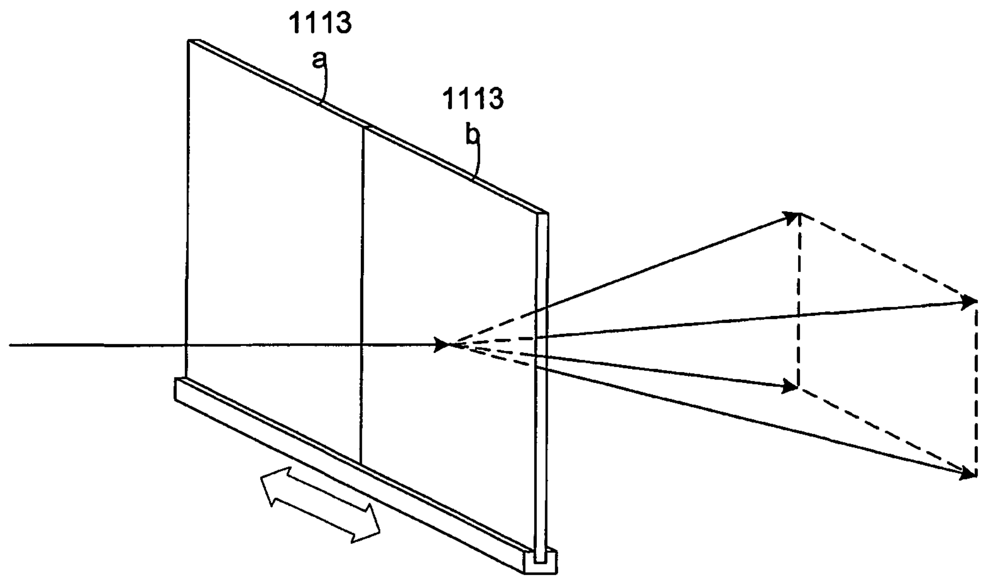

Fig. 52

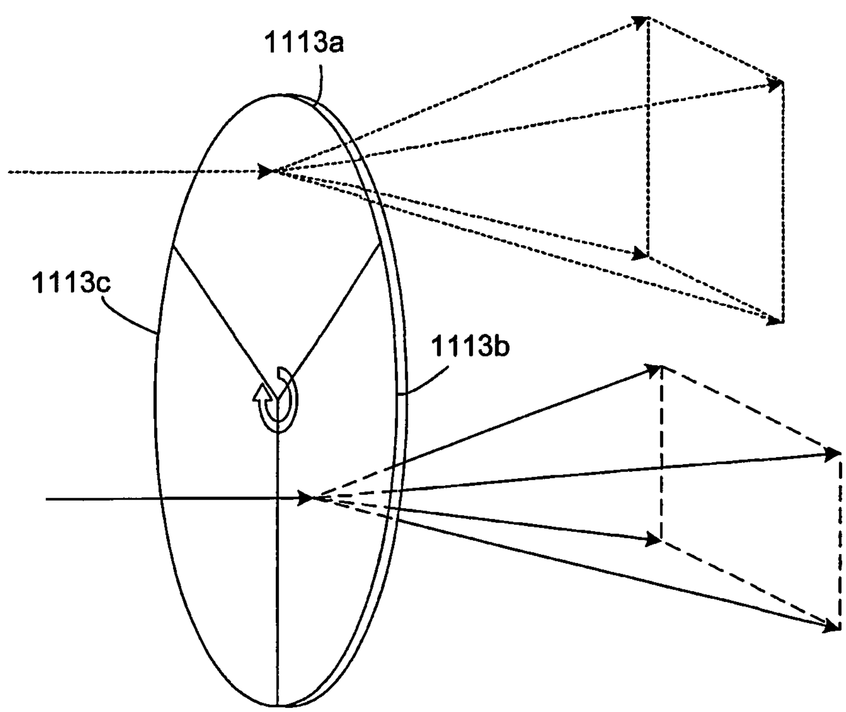

Fig. 53